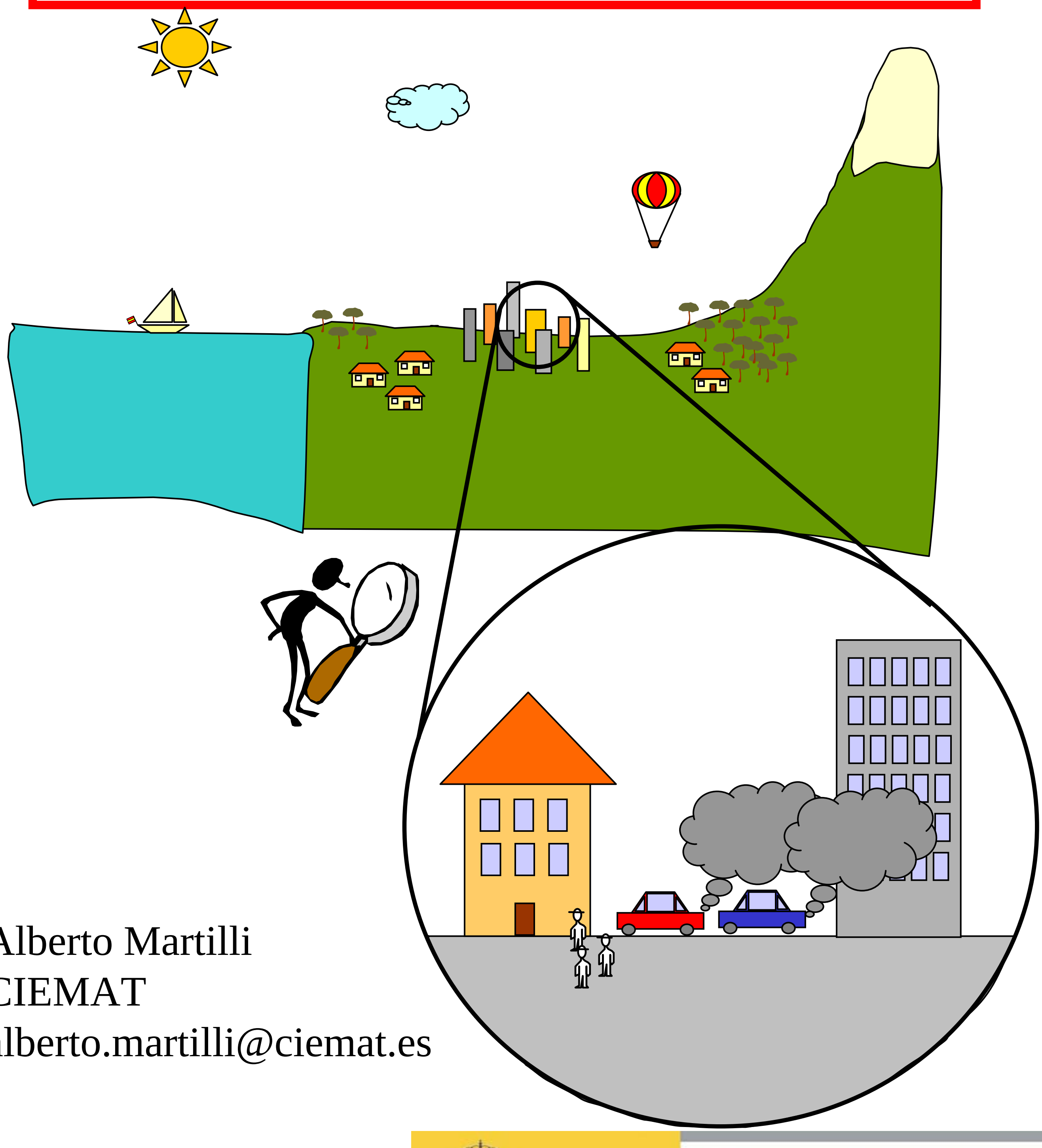
High resolution simulations of the interactions between urban canopy and Boundary Layer



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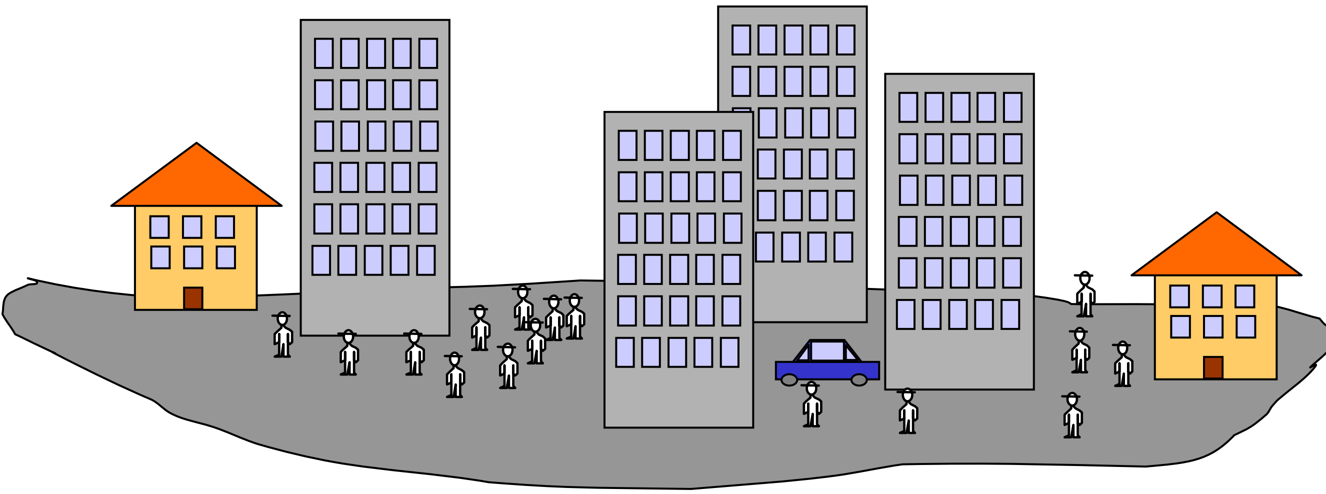
Why is the Urban Canopy Layer (UCL) important ?



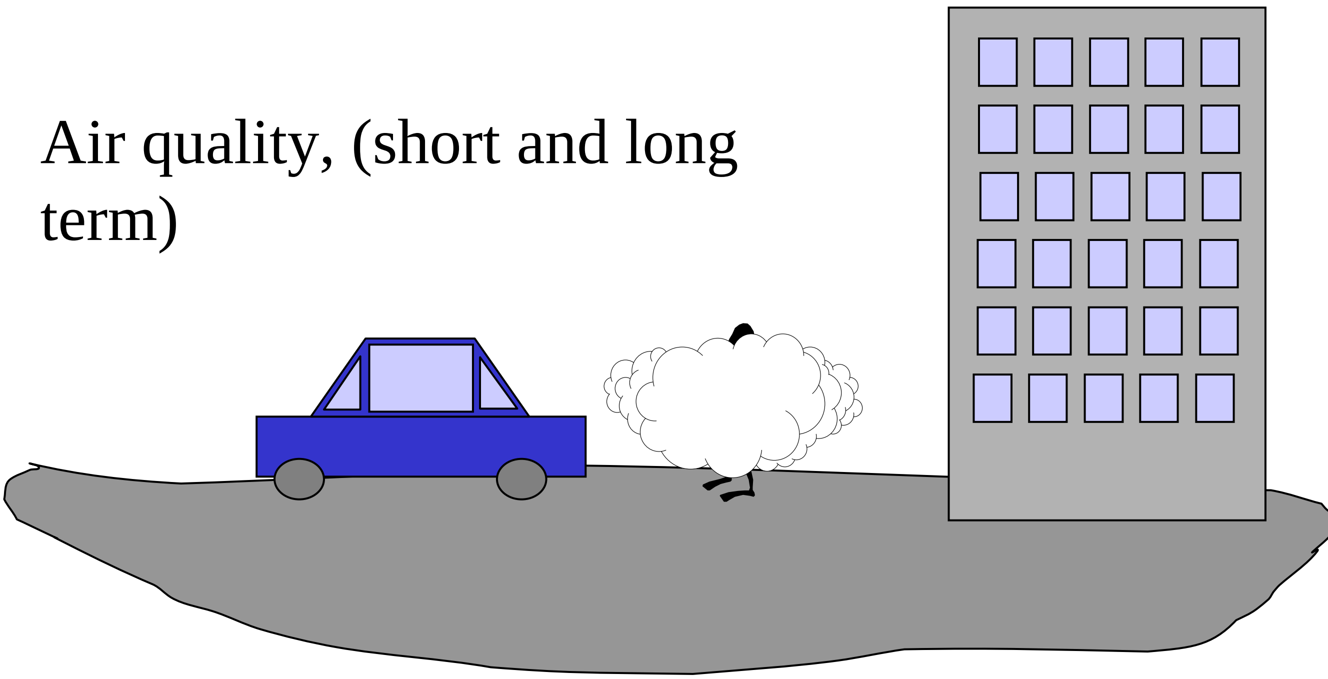
Many people live in the UCL

Mexico city, population more than 20 million

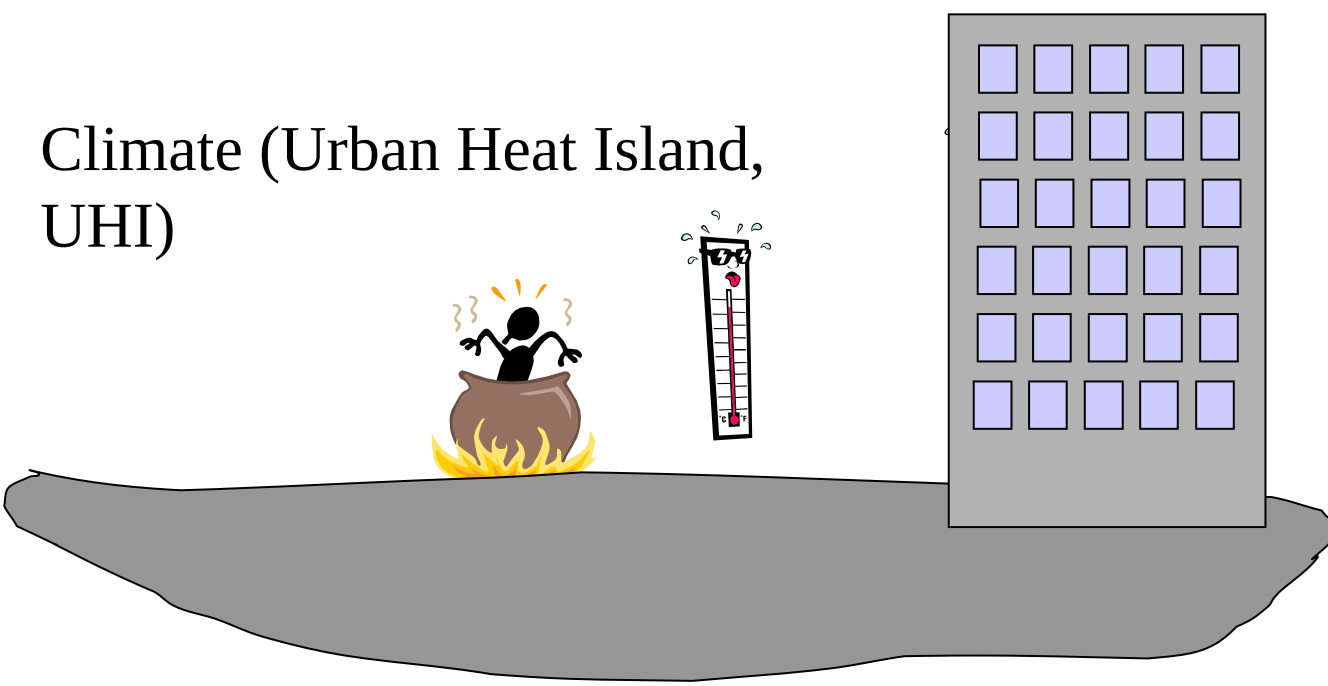
Around half of the global population lives in cities and is forecast to increase to three quarters during the next twenty five years

How does UCL air affect people's life?

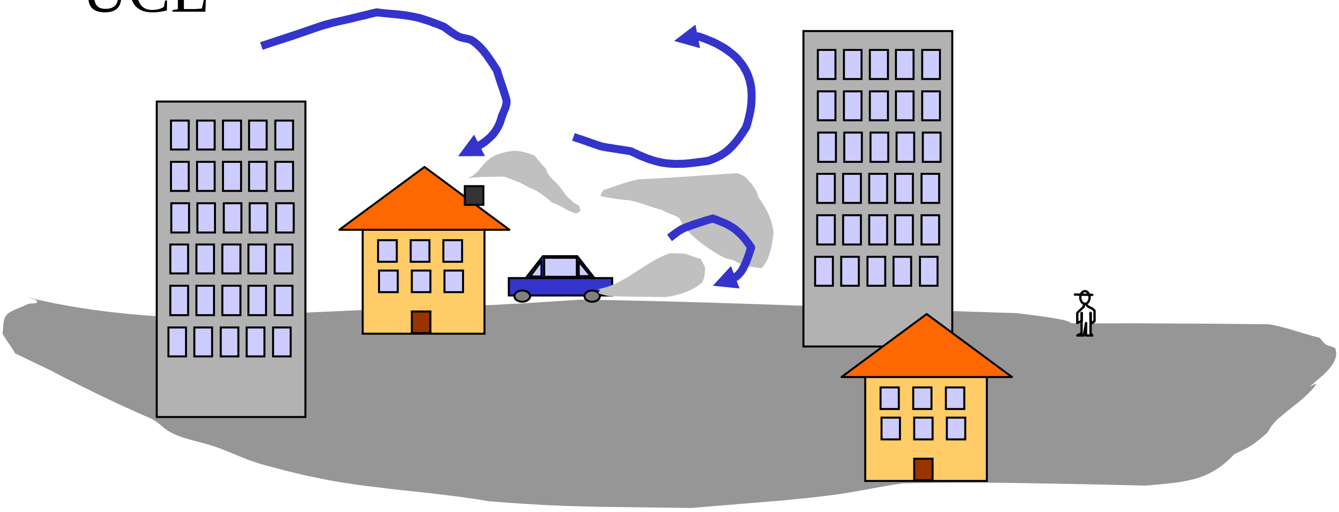
Air quality, (short and long term)



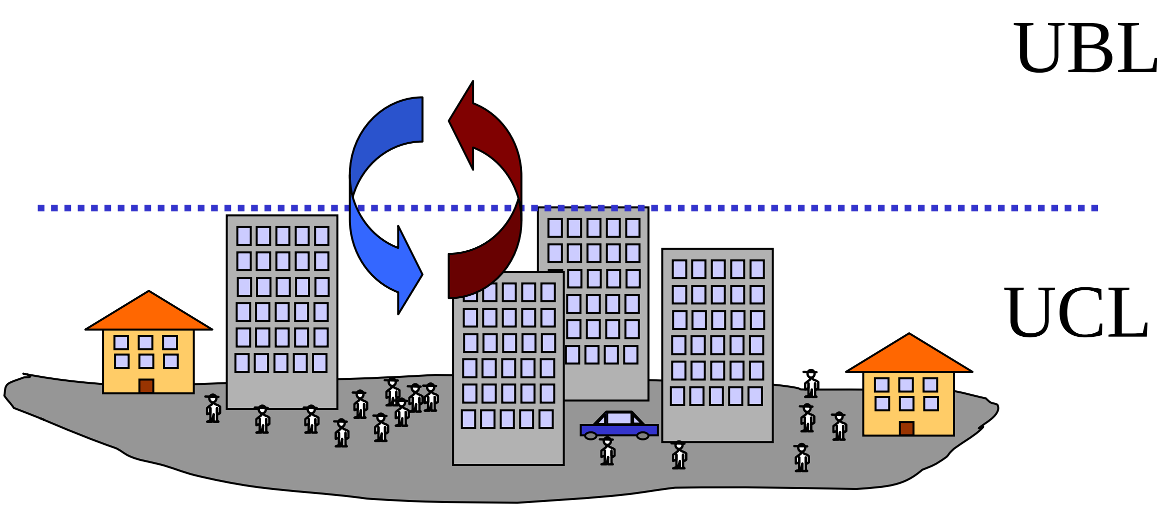
Climate (Urban Heat Island, UHI)



Factors determining air pollutant concentration in UCL

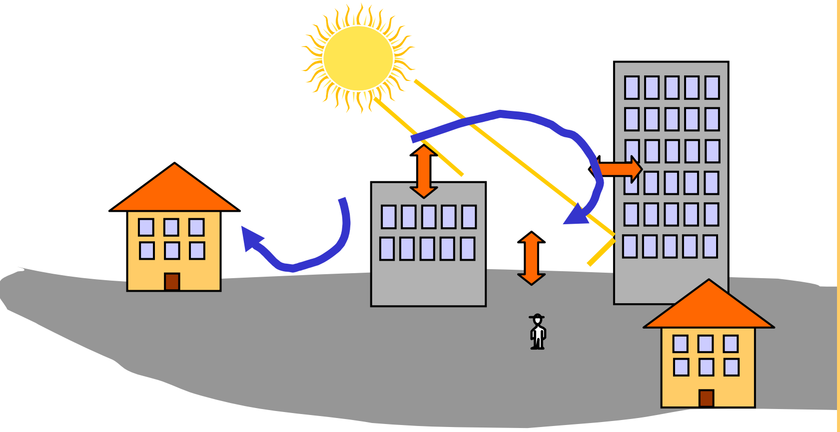


Emissions, dispersion within the UCL



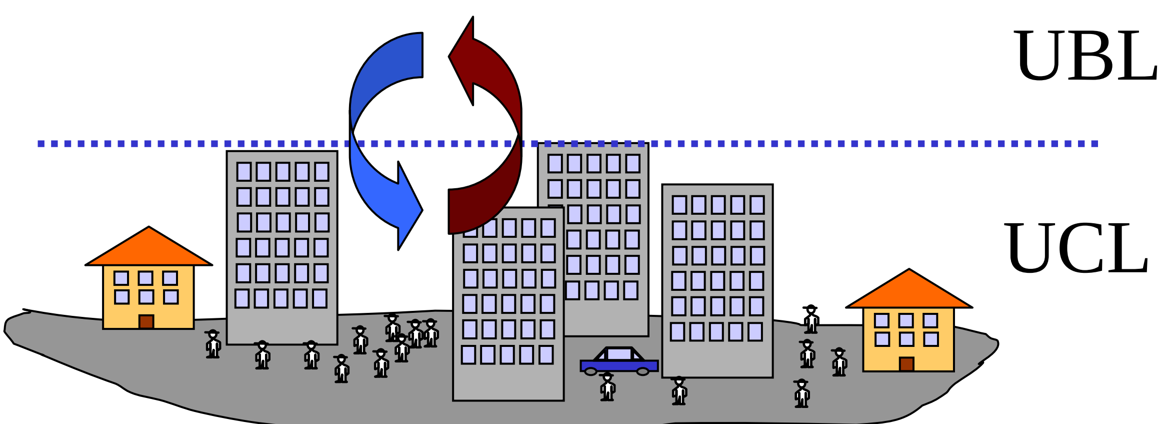
Exchanges between UCL and Urban Boundary Layer (UBL) above

Factors determining air temperature in UCL



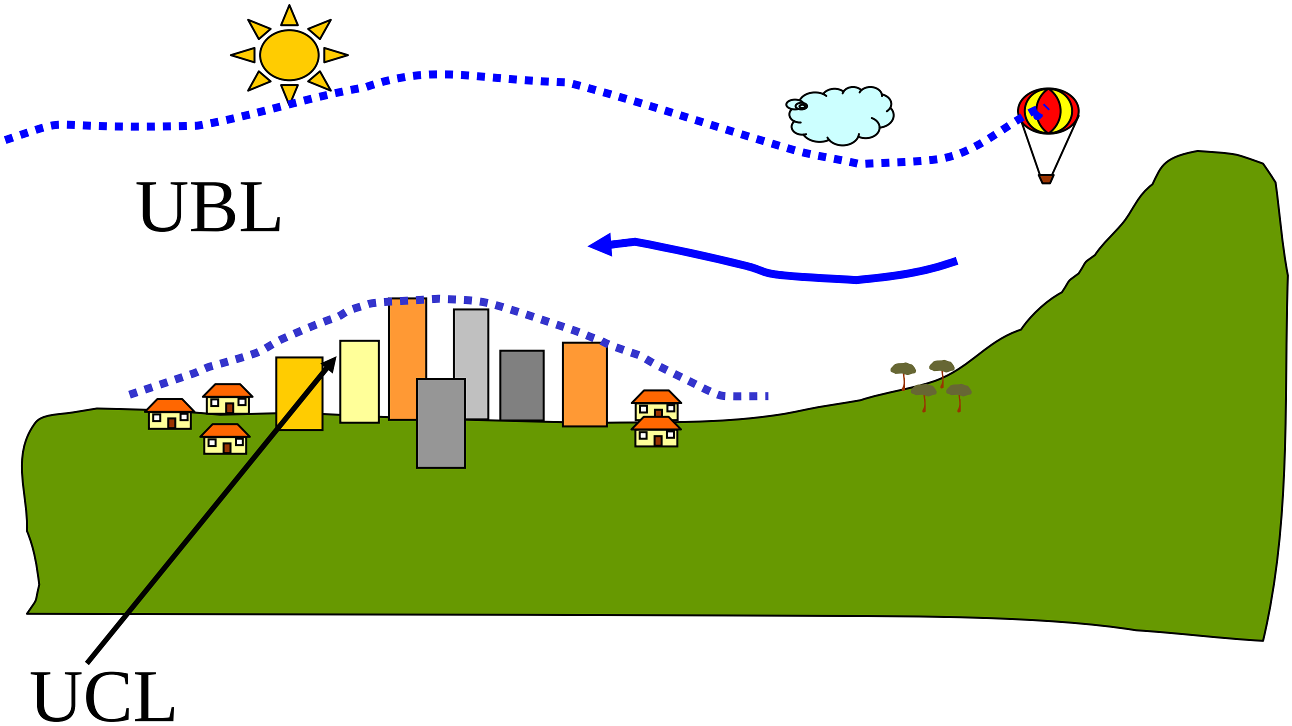
Energy budget from many surfaces with different thermal properties. Trapping of radiation in street canyons. Lack of vegetation

Heat fluxes from urban surfaces, and anthropogenic heat fluxes. Dispersion of heat within UCL



Exchanges between UCL and UBL

Air pollutants and temperature in the UBL can be advected from other parts of the city, or from rural areas



On the other hand, UBL structure is determined by UCL (e. g. heat fluxes, turbulence) and boundary layer formed around the city

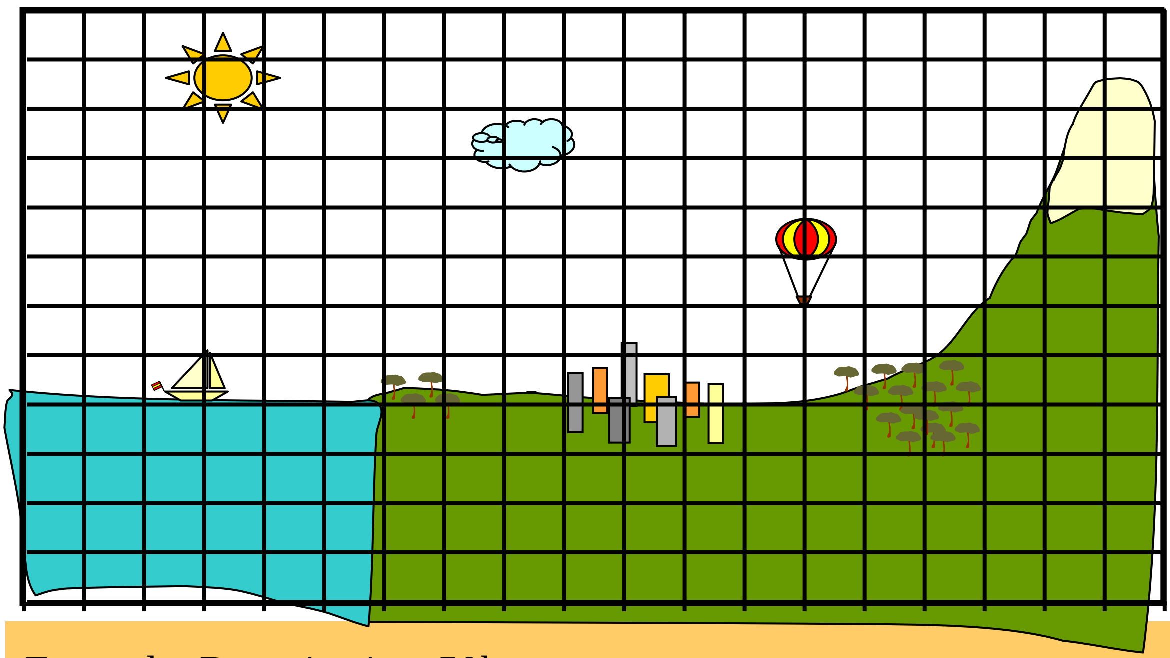
UBL and UCL are closely linked and must be considered together. To account for UBL, an horizontal scale larger than the city must be considered (mesoscale).

The phenomena involved are complex and non-linear.

To investigate UCL and evaluate strategies to improve air quality and microclimate in UCL, the best tool is a numerical model.

Such model must be able to reproduce at best wind, temperature and turbulence fields in the UCL and UBL (for air pollution such fields are used by a dispersion model).

For computational reasons, it is not possible to build a model able to resolve every building and at the same time have a domain large enough to represent urban-rural interactions.

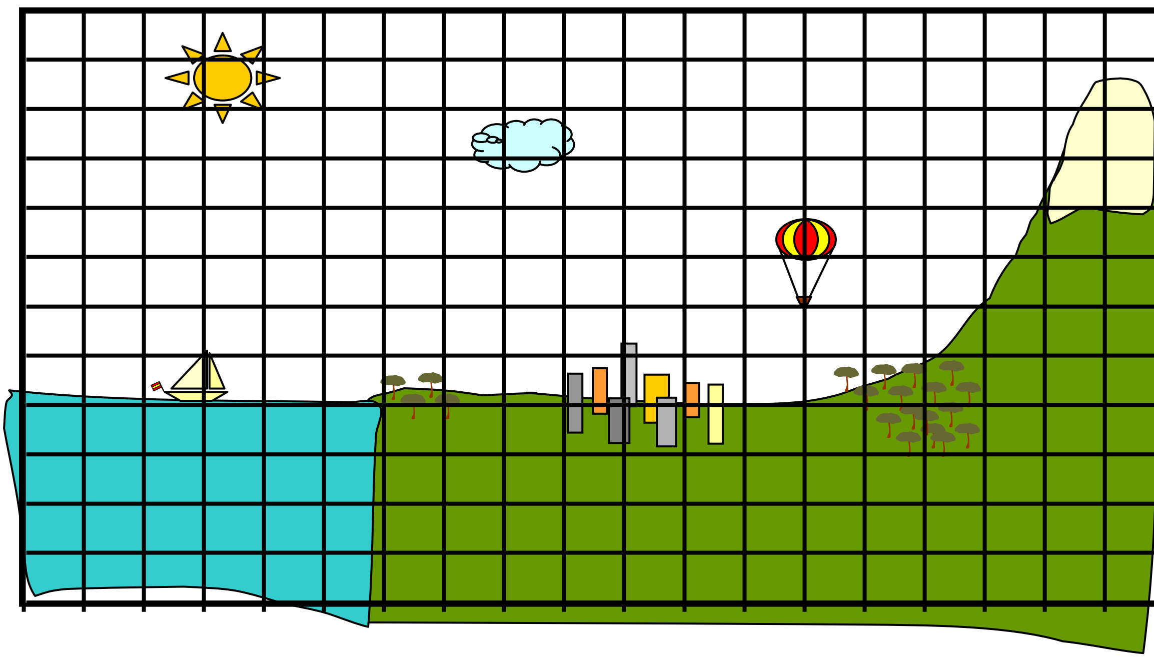


Example: Domain size: 50km
High resolution mesoscale simulations performed today:
DX=DY=1km=> nx=50, ny=50
DZ stretched, nz=50,
DT=30s.
For 1 hour (nx*ny*nz)*3600./Dt =1.5 10^7 calculations are needed.

To resolve the buldings, DX=DY=1m, DT=0.003s,
Without modifying the DZ, for 1 hour 10^{16} calculations are needed.

To resolve the buildings and have a domain size large enough, we need a computer 10^9 faster than todays computers !

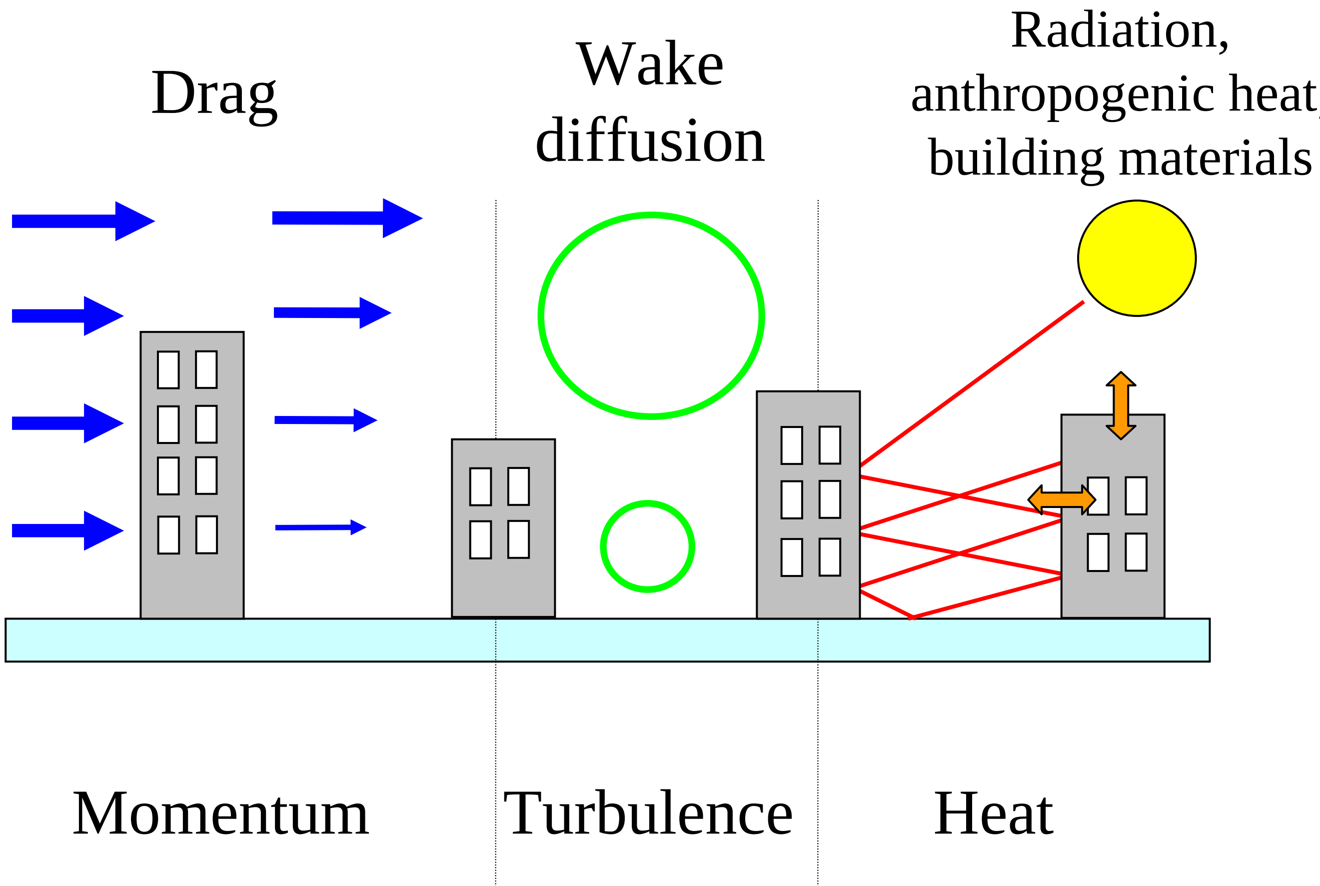
So, the most common approach is to use mesoscale models at high resolution (1km or several hundreds of meters), and parameterize the impact of the city on wind, turbulence and heat fluxes.

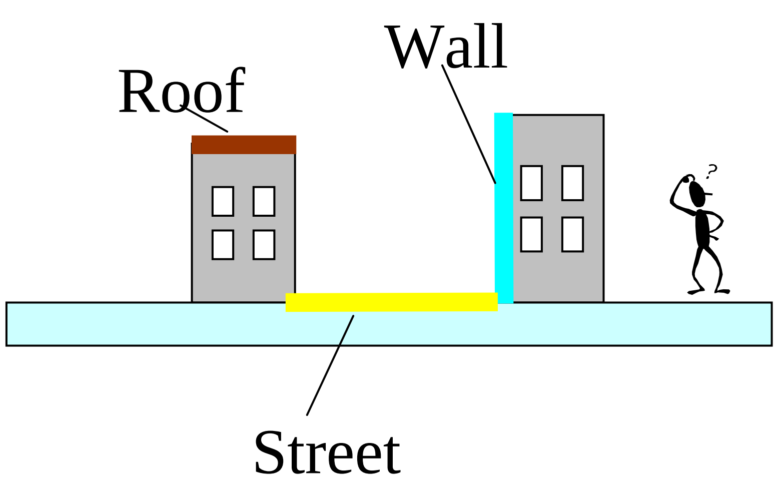


The key in such modelling is the representation of the urban effects on the airflow.

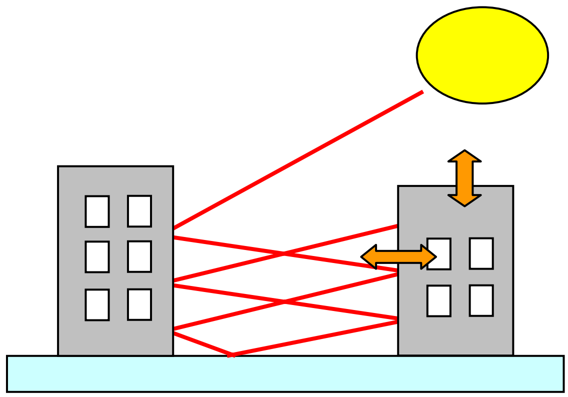
Which are those effects?

The most important urban effects are

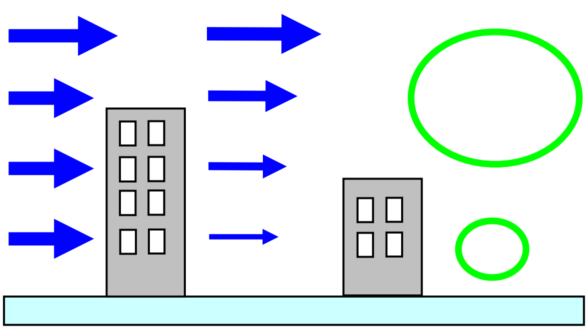




It is possible to group such effects in:



Thermal (on temperature)



Dynamical (on momentum and TKE)

In recent years, also thank to the continous increase of CPU power, several approaches have been proposed to account for such effects in mesoscale models.

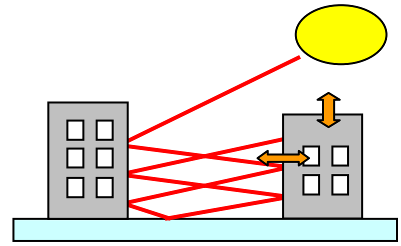
In the rest of the presentation we will see:

- Techniques used to parametrize urban thermal effects
- Future directions. Account for Building Energy.

- Techniques used to parameterize urban dynamical effects
- Analysis of CFD results from an urban parameterization perspective.

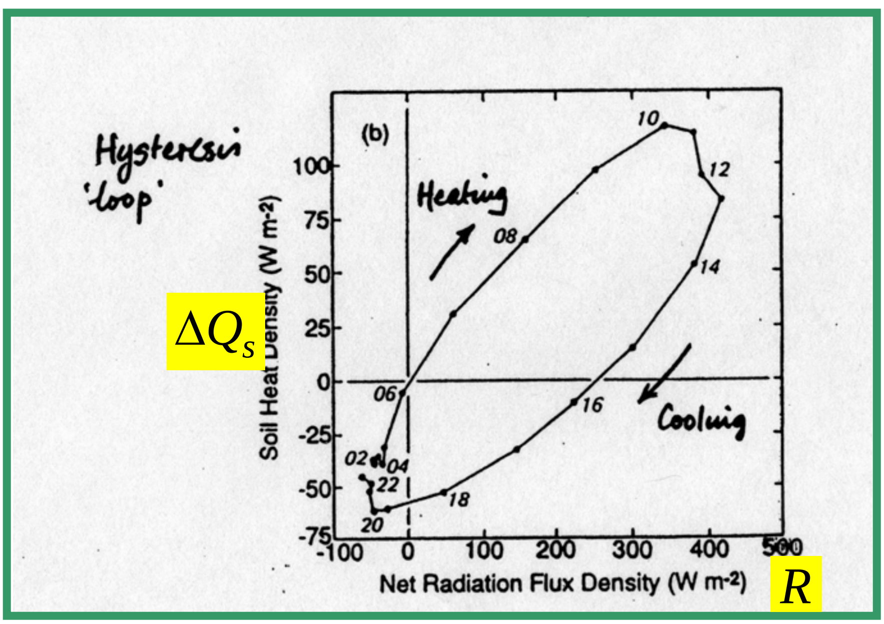
- Idealized simulations of the impact of urban canopy on UBL structure.

Thermal effects



Semi-empirical approach

Objective Hysteresis Model (OHM Grimmond et al., 1991). Reasonable expectation that ΔQ_S (storage) is a fraction of R (net all-wave radiation). A daily plot of ΔQ_S vs R results in a hysteresis loop



H. Taha (1999) implemented OHM in a mesoscale model

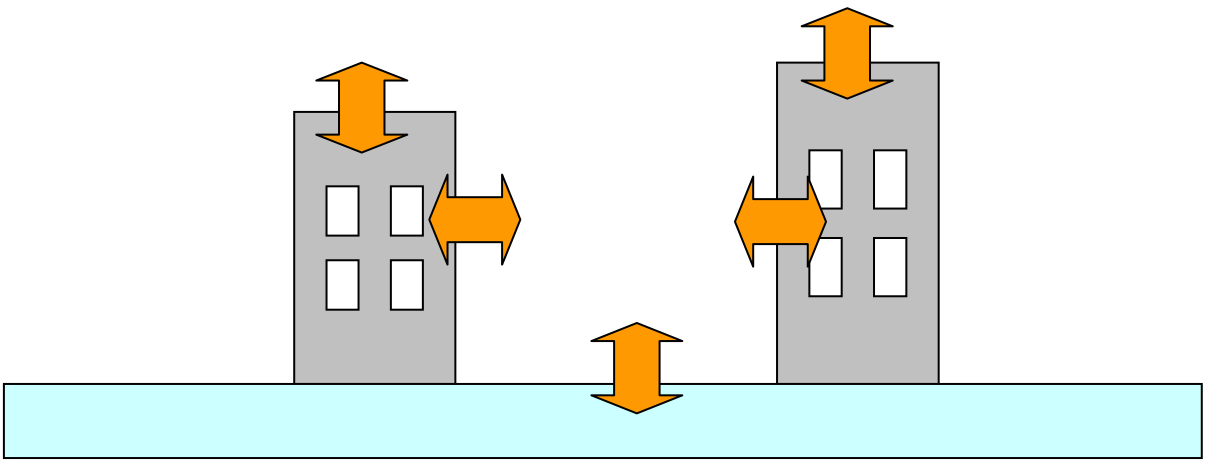
Changing the coefficents, it can work for any surface.

$$\Delta Q_s = a_1 R + a_2 \frac{\partial R}{\partial t} + a_3$$

Problem: a long series of data is needed to find the parameters a_1, a_2, a_3.

Physically based approaches

Weigthed average of fluxes from different urban surfaces (road, wall, roof) (Masson 2000, Kusaka et al. 2001, Martilli et al.2002).



$$H_{r,w,s} = -C_{r,w,s}\left(T_{air} - T_{r,w,s}\right)$$

$$H_{r,w,s} = heat\ \ flux$$

r=roof,
s=street
w=wall

$C_{r,w,s}$ is a coefficient function of wind speed and surface roughness. Usually it takes into account atmospheric stability for horizontal surfaces, but not for vertical surfaces.

Surface temperatures (T_s) are estimated solving an energy budget at each surface.

$$\frac{\partial T_s}{\partial t} = \frac{\left(R - (H + G + L\right)}{C_s \Delta z_s}$$

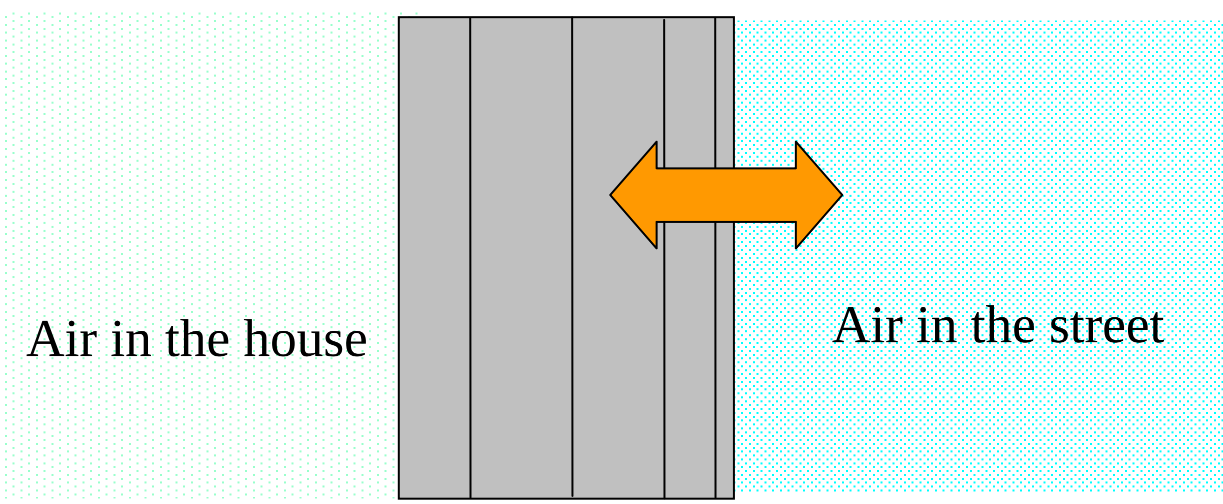
Radiative fluxes are positive if directed toward the surface. Non-Radiative fluxes are positive if directed away from the surface

R=short and longwave radiation
G=heat diffused in the material
H=sensible heat flux to the atmosphere
L=latent heat fluxes (only in Masson 2000, and Kusaka et al. 2001).
Cs= specific heat of material, Δz_s depth of the material layer

G is estimated by solving an heat diffusion equation in several layers in the material (wall, roof, street).

$$\frac{\partial T_i}{\partial t} = \frac{\partial}{\partial z}\left(K_s \frac{\partial T_i}{\partial z}\right)$$

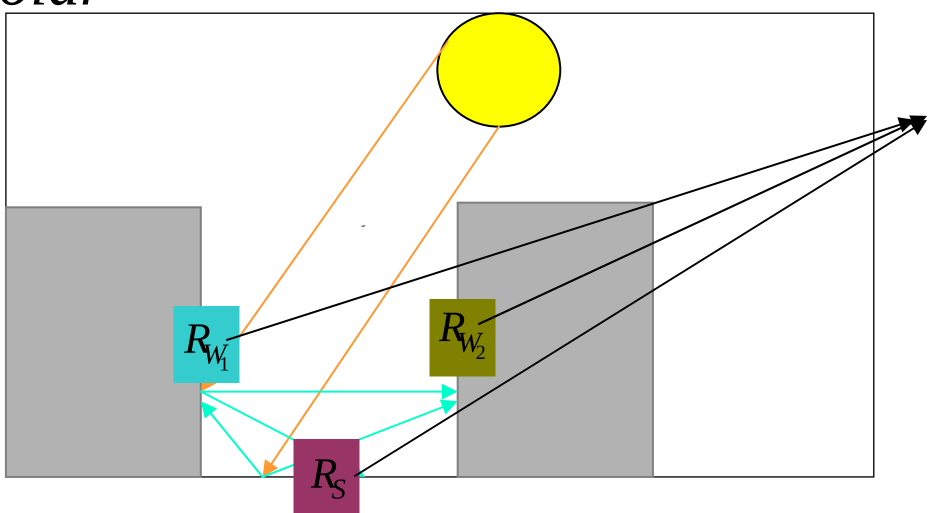
K_s=thermal conductivity of the material
T_i=temperature of the ith layer in the material



It is strongly affected by the thermal properties of the materials, and (for roof and walls) by the air temperature in the house

Radiation is composed by short (solar), and long (infrared) waves. For walls and street radiation trapping must be considered.

Solar



Short wave radiation reaching the surface

Basic idea

Isotropic reflection

$$R_{W_1} = R_{WD_1} + \alpha_S \Psi_{SW} R_S + \alpha_W \Psi_{WW} R_{W_2}$$
$$R_{W_2} = R_{WD_2} + \alpha_S \Psi_{SW} R_S + \alpha_W \Psi_{WW} R_{W_1}$$
$$R_S = R_{SD} + \alpha_W \Psi_{WS} R_{W_1} + \alpha_W \Psi_{WS} R_{W_2}$$

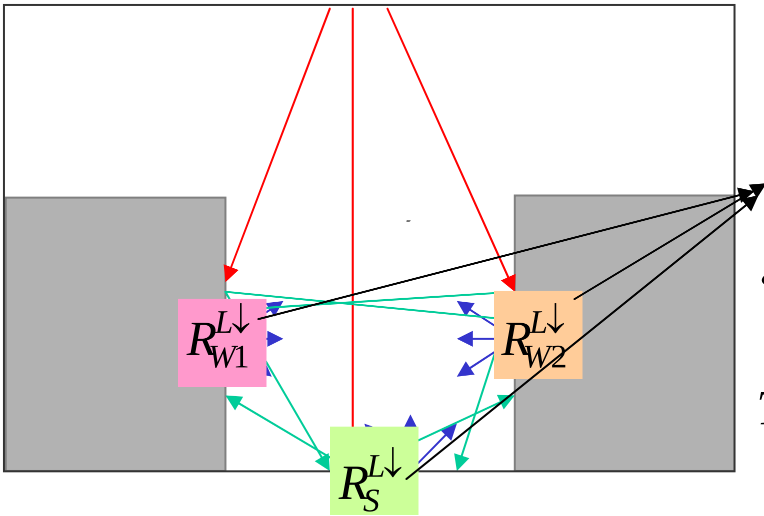
3 equations
3 unknonwn

$R_{WD_1}, R_{WD_2}, R_{SD} =$ Incident radiation at walls and street function of the solar zenith angle and street orientation.

$\alpha_W, \alpha_S =$ Albedo of wall and street

$\Psi_{SW}, \Psi_{WS}, \Psi_{WW} =$ View factors street-to-wall,wall-to-street,wall-to-wall. View factor from surface A to surface B, is defined as the fraction of radiative energy leaving surface A that reaches surface B

Longwave $$R^{L} = R^{L\downarrow} - \varepsilon\sigma T_S^4$$



Long wave radiation reaching the surface

$\varepsilon_W, \varepsilon_S$ Emissivity of wall and street

T_{W1}, T_{W2}, T_S Surface temperture of walls and street

$$R_{W1}^{L\downarrow} = R_{WD1}^{L\downarrow} + \Psi_{SW}\left(\varepsilon_S \sigma T_S^4 + (1-\varepsilon_S) R_S^{L\downarrow}\right) + \Psi_{WW}\left(\varepsilon_W \sigma T_{W2}^4 + (1-\varepsilon_W) R_{W2}^{L\downarrow}\right)$$

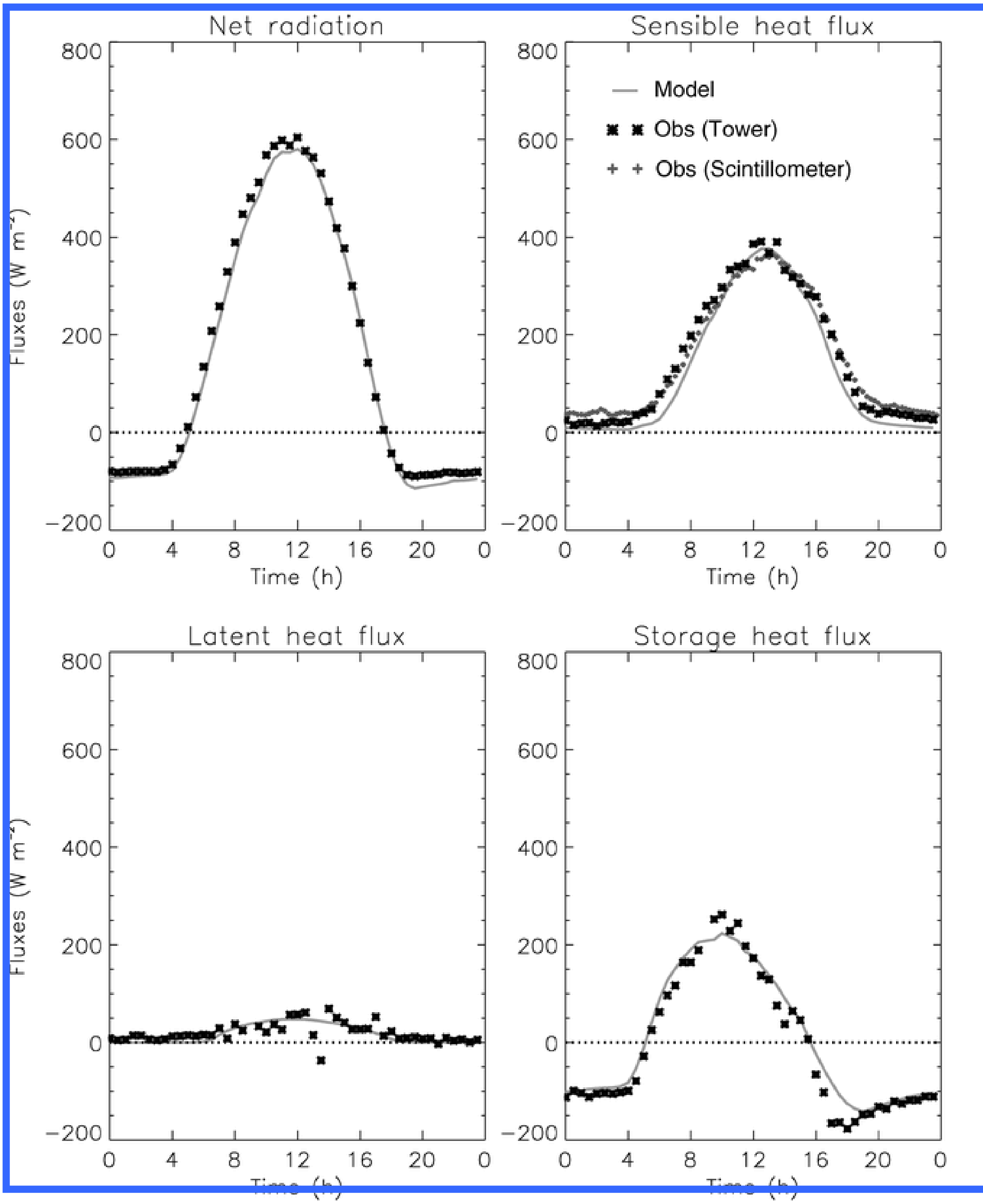
$$R_{W2}^{L\downarrow} = R_{WD2}^{L\downarrow} + \Psi_{SW}\left(\varepsilon_S \sigma T_S^4 + (1-\varepsilon_S) R_S^{L\downarrow}\right) + \Psi_{WW}\left(\varepsilon_W \sigma T_{W1}^4 + (1-\varepsilon_W) R_{W1}^{L\downarrow}\right)$$

$$R_S^{L\downarrow} = R_{SD}^{L\downarrow} + \Psi_{WS}\left(\varepsilon_W \sigma T_{W1}^4 + (1-\varepsilon_W) R_{W1}^{L\downarrow}\right) + \Psi_{WS}\left(\varepsilon_W \sigma T_{W2}^4 + (1-\varepsilon_W) R_{W2}^{L\downarrow}\right)$$

Differences between the schemes:
Masson (2000) integrates over all the possible streets directions
Kusaka et al. (2001) and Martilli et al. (2002) consider predominant streets directions
Martilli et al. (2002) consider several numerical levels in the canopy and vertical distribution of buildings heights.

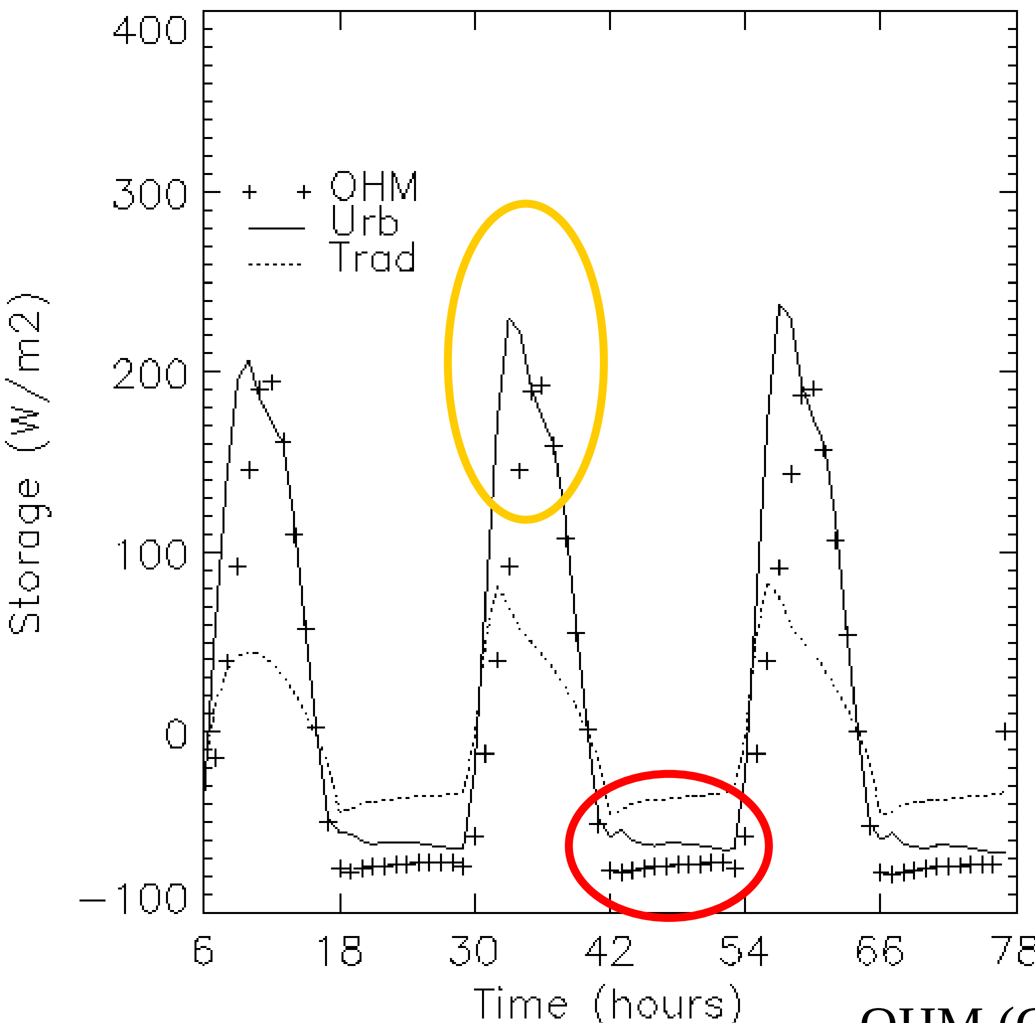
Validations

Masson 2000 over Marseille (from Lemonsu et al. 2004)



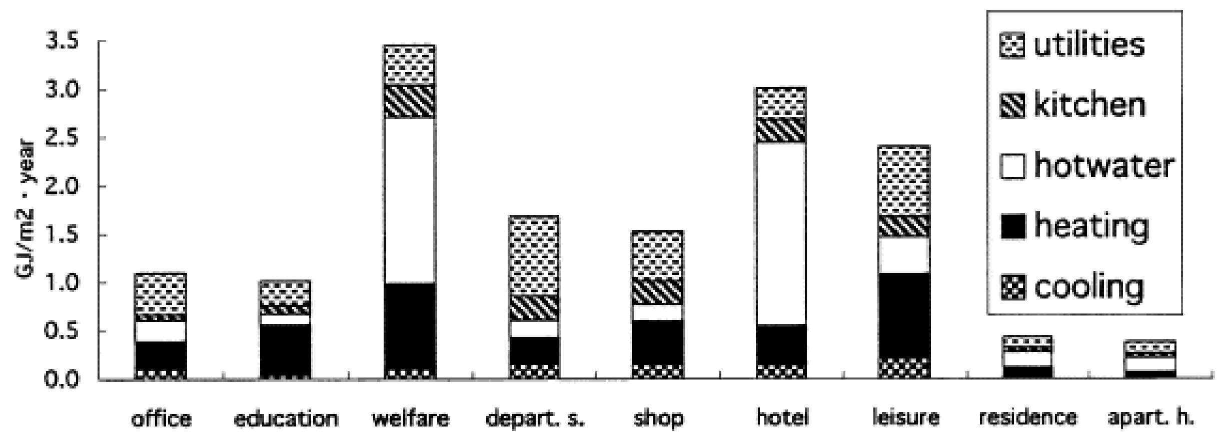
Validations

Storage term (from Martilli et al. 2002)



OHM (Grimmond et al. 1991)

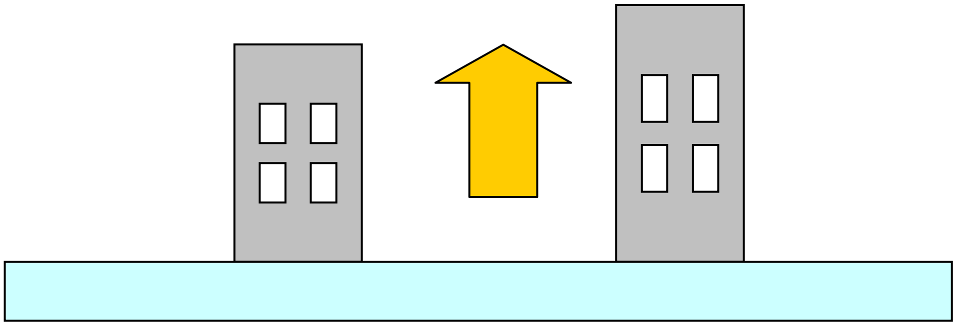
Moreover there are additional anthropogenic sources of heat.



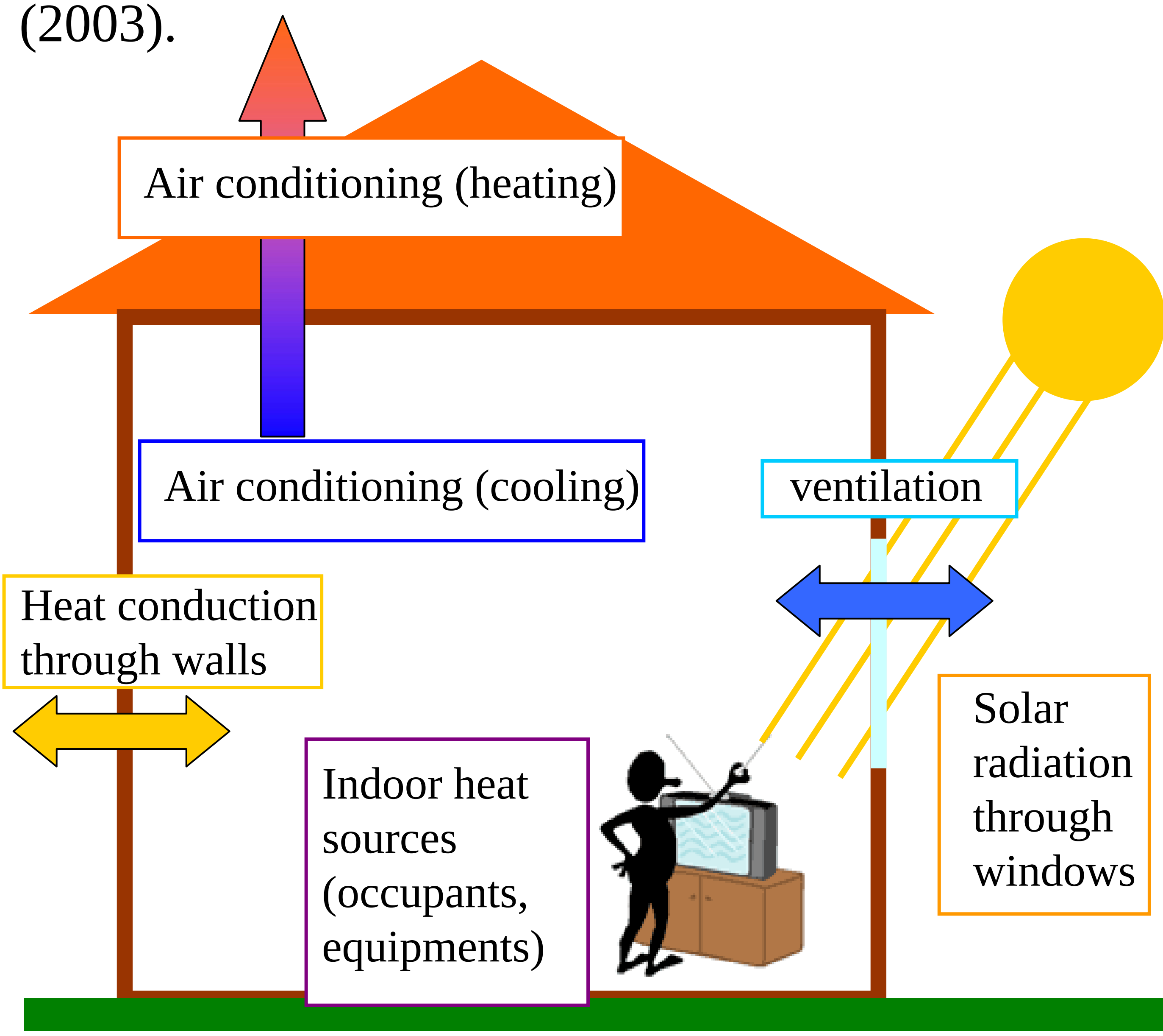
From Ichinose et al. 1999 for Tokyo

In limited areas, they can reach peaks of hundreds of W/m^2 . Of the same order of the the solar radiation.

Injected as a source term in the atmosphere



A step forward to evaluate energy fluxes in urban areas. Account for Building Energy. An example, inspired to Kikegawa et al. (2003).



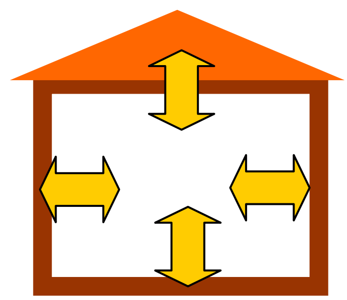
Important in estimates of energy savings for UHI mitigation strategies.

The air temperature in the building T_r is estimated from

$$\frac{\partial T_r}{\partial t} = \frac{H_{in.surf} + H_{vent} + H_{eq.} + H_{occ.} + H_{a.cond.}}{V_{air}\rho C_P}$$

Sensible heat exchanged between internal surfaces (walls, pavements, roofs) and internal air.

$$H_{in.surf} = \sum_i A_{wi} C_{wi} \left(T_{wi} - T_r \right)$$



A_{wi} = area of the surface
C_{wi} = exchange coefficient
T_{wi}= internal surface temperature.

To estimate the surface temperature an energy budget is solved at the internal surfaces, accounting for solar radiation entering from windows.

The walls and roof temperature calculation can be coupled with the one presented before.

Exchange of heat between the interior and exterior of the buildings through exchange of air masses.

$$H_{vent} = C_p \rho V_a (T_a - T_r)$$

T_a = external air temperature.

V_a = ventilation rate.

Ventilation rate is a function of window opening, infiltration, architecture, wind speed, temperature difference between interior and exterior.

Wind towers in Yazd, Iran

‘Collateral’ importance of this term:

- Potential for natural cooling ventilation systems
- Exchanges of pollutants outdoor-indoor.

Sensible heat generated by equipments

$$H_{eq} = \sum_j \varphi_j^e(t) q_j^e$$

q_j^e Energy generated by the equipment

$\varphi_j^e(t)$ Period of use the equipment

Sensible heat generated by occupants

$$H_{occ} = \varphi^o(t) q^o$$

q^o Energy generated by one occupant

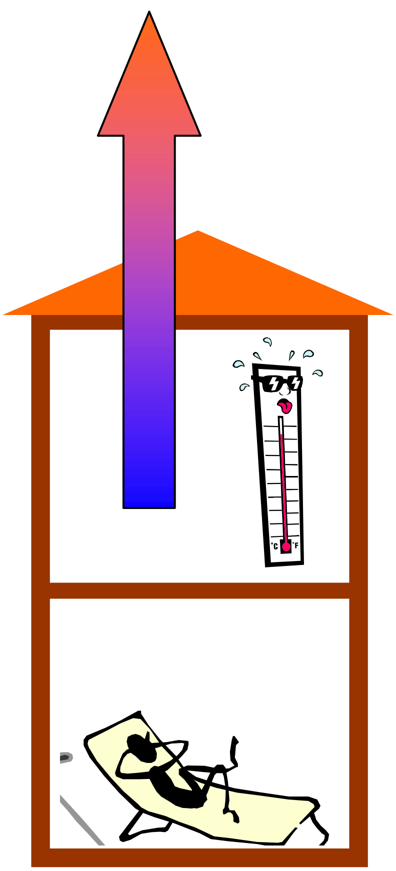
$\varphi^o(t)$ Number of occupants as a function of time

Air conditioning pumps heat from inside to outside the building. Assuming a full air conditoning case, the internal air temperature is constant. So

$$H_{a.cond.} = -\left(H_{in.surf} + H_{vent} + H_{eq.} + H_{occ.}\right)$$

If COP is the energy efficiency of the air conditioning system, the cooling energy consumption is

$$E_C = \frac{H_{a.cond.}}{COP}$$

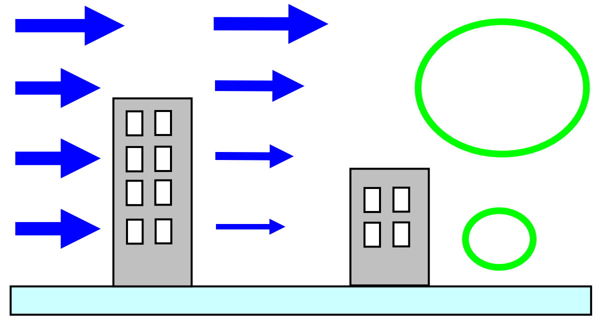


And the waste heat emission (heat input to the atmosphere) is

$$Q_A = E_C + H_{a.cond.} = \frac{COP}{COP+1} H_{a.cond}$$

Break ?

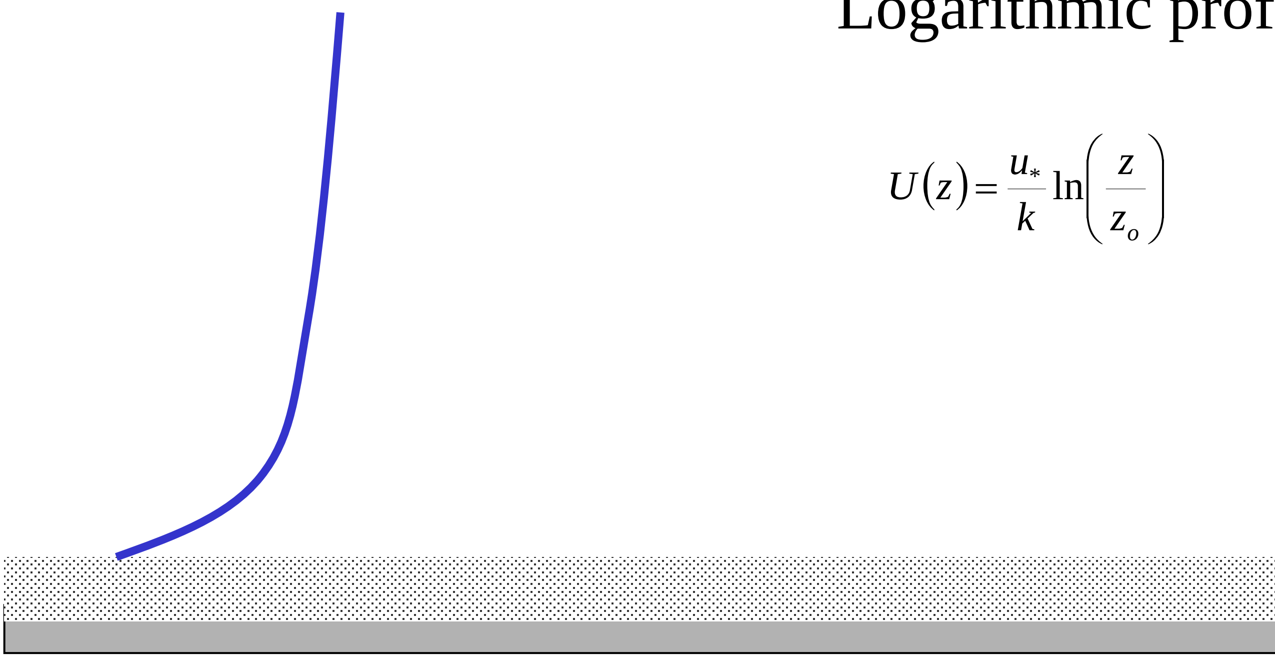
Dynamical effects



Traditional method.

Logarithmic profile

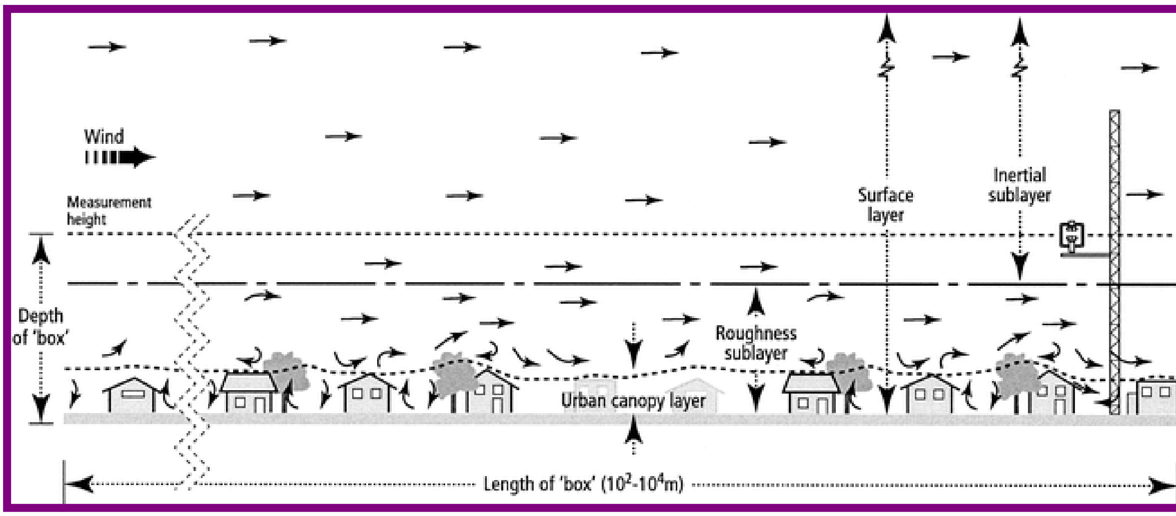
$$U(z) = \frac{u_*}{k} \ln\left(\frac{z}{z_o}\right)$$

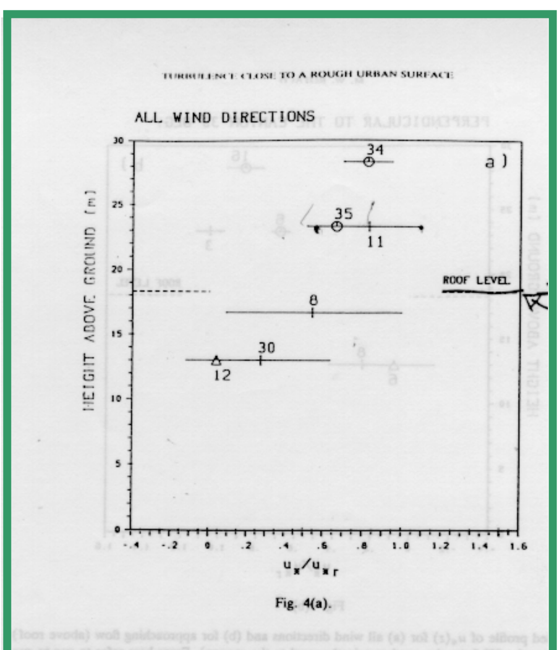


Roughness length (z0)~of 1-3 m,. Based on similarity theory that assumes that turbulent fluxes are constant with height in the surface layer.

However....

Turbulent fluxes are not constant with height (Rotach 1993) in the Urban Roughness Sublayer (1-3 times mean building heigth). The similarity theory cannot be applied.





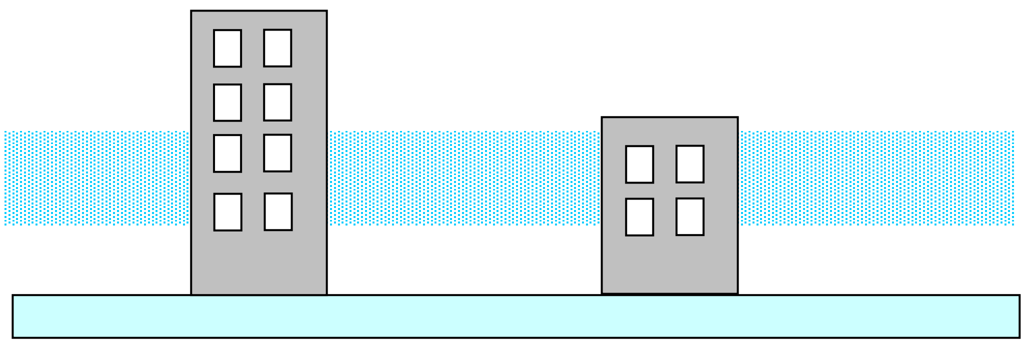
Zurich, Switzerland

Rotach, 1993

To parameterize the canopy it is common to use a drag (or porosity) approach, mutuated from vegetation canopy modelling

Mathematical formulation

Consider a volume of air within the urban canopy (e. g. the grid cell of the model)



the spatial average of a flow quantity over the volume is

$$\langle \phi \rangle = \frac{1}{V} \int_V \phi(x) dV$$

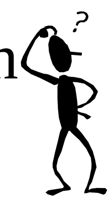
Then the fluctuation from the average is

$$\tilde{\phi}(x) = \phi(x) - \langle \phi \rangle$$

So, the spatially-averaged Navier-Stokes equations become

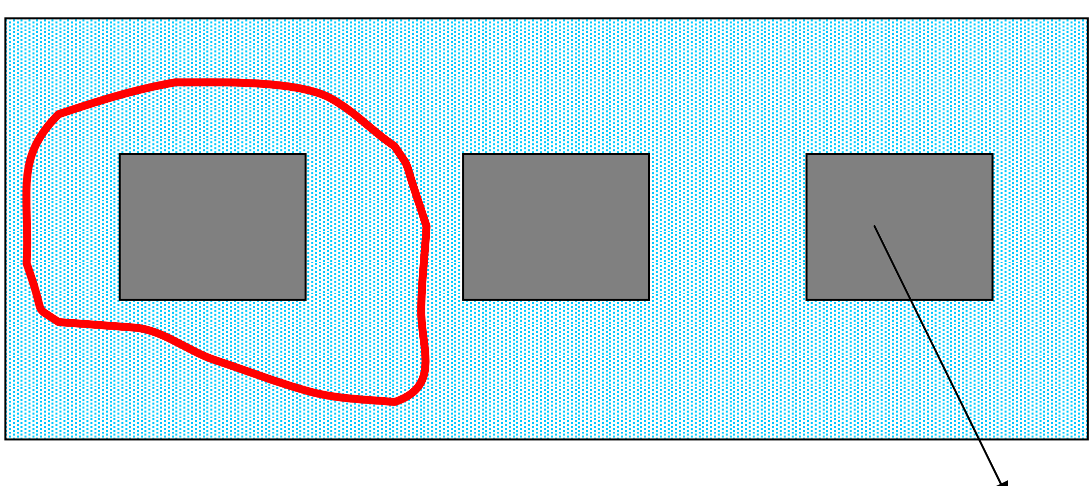
$$\frac{\partial \langle u_i \rangle}{\partial t} = -\frac{\partial \langle u_i \rangle \langle u_j \rangle}{\partial x_j} - \frac{1}{\rho}\frac{\partial \langle p \rangle}{\partial x_i} - \boxed{\left\langle \frac{\partial \tilde{p}}{\partial x_i} \right\rangle} - \frac{\partial \langle \tilde{u}_i \tilde{u}_j \rangle}{\partial x_j}$$

This term is not zero because the volume is not simply connected. If the volume is not simply connected, derivation and integration do not commute



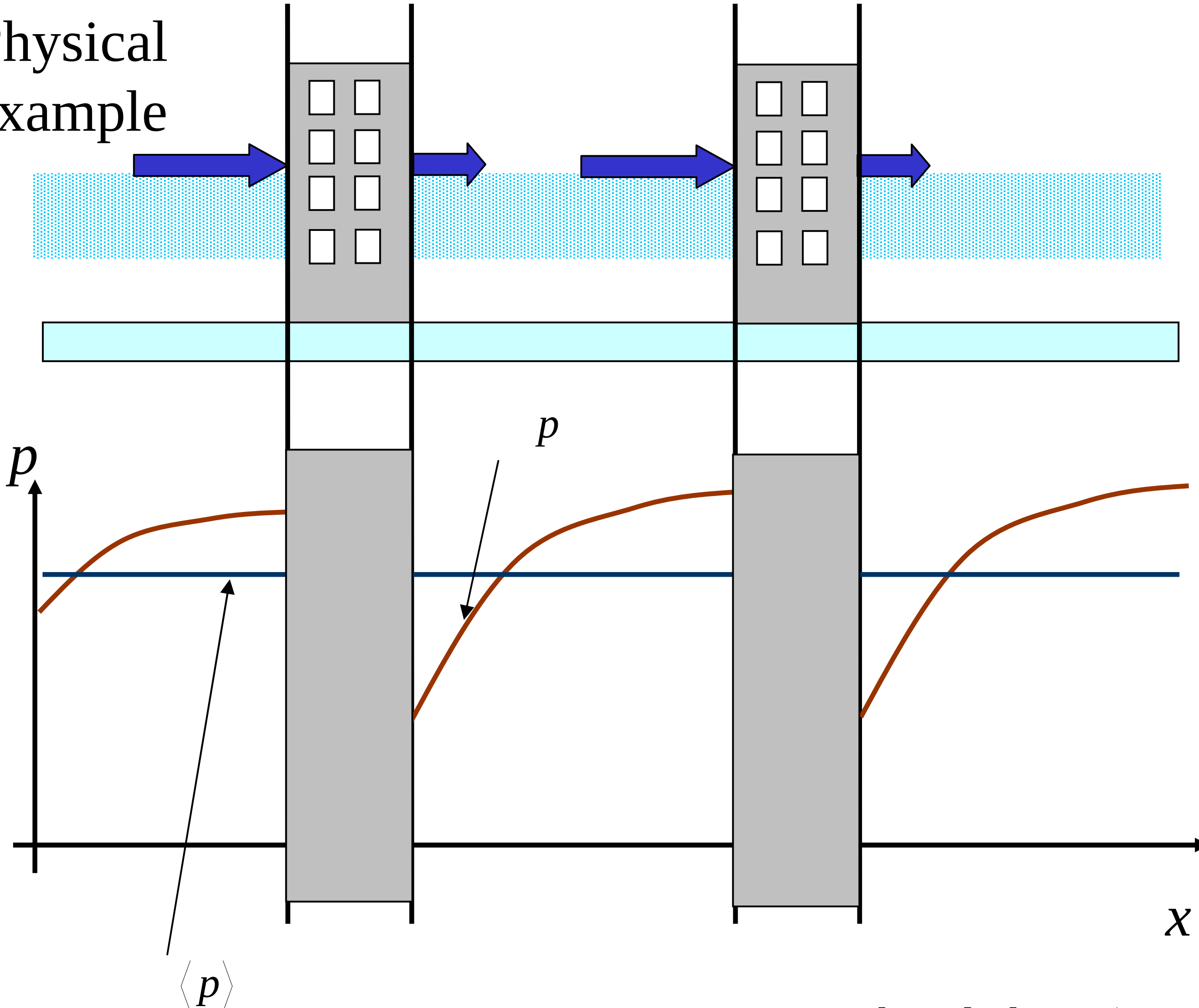
Def. simply connected= property of a surface or other space such that any closed curve within it can be continuously shrunk to a point without leaving the space.

View from the top



building

Physical example



Raupach and Shaw, (1982)

$$\langle \tilde{p} \rangle = 0 \Rightarrow \frac{\partial \langle \tilde{p} \rangle}{\partial x_i} = 0$$

$$\frac{\partial \tilde{p}}{\partial x_i} > 0 \Rightarrow \frac{1}{V}\int_V \frac{\partial \tilde{p}}{\partial x_i} dV \neq 0$$

$$\left\langle \frac{\partial \tilde{p}}{\partial x_i} \right\rangle \neq \frac{\partial \langle \tilde{p} \rangle}{\partial x_i}$$

Integral and derivative do not commute

$$\left\langle \frac{\partial \tilde{p}}{\partial x_i} \right\rangle = \frac{1}{V}\int_V \frac{\partial \tilde{p}}{\partial x_i} dV = \frac{1}{V}\int_S \tilde{p} n_i da$$

Link with pressure fluctuation on building surfaces (Gauss theorem)

Approaches to parameterize this term are mutuated from vegetation canopy modelling. Small differences between the approaches.

i=1,2, e. g. the drag force is horizontal

Uno et al., 1989

$$\left\langle \frac{\partial \tilde{p}}{\partial x_i} \right\rangle = -\rho C_d \eta a(z) \langle u_i \rangle \left(\langle u_1 \rangle^2 + \langle u_2 \rangle^2 \right)^{1/2}$$

a(z)=building surface area density, η fraction of building area, C_d=0.1

Sievers, 1990

$$\left\langle \frac{\partial \tilde{p}}{\partial x_i} \right\rangle = -\rho C_d w_f \langle u_i \rangle |\langle \vec{u} \rangle|$$

w_f wall area density, C_d=0.2

Brown and Williams, 1998

$$\left\langle \frac{\partial \tilde{p}}{\partial x_i} \right\rangle = -\rho f_{roof} C_d a(z) \langle u_i \rangle |\langle u_i \rangle|$$

f_{roof}=horizontal fraction of model grid covered by buildings, a(z)building surface area density

Martilli et al. 2002,

$$\left\langle \frac{\partial \tilde{p}}{\partial x_i} \right\rangle = -\rho C_d \frac{S_w}{V_{air}} \langle u_i^{ort} \rangle |\langle u_i^{ort} \rangle|$$

S_w wall surface in the cell, V_{air}=air volume of the cell, u^{ort}= wind component ortogonal street direction, C_d=0.4

Coceal and Belcher 2004

$$\left\langle \frac{\partial \tilde{p}}{\partial x_i} \right\rangle = -\rho C_d \frac{\lambda_f}{(1-\beta)} \langle u_i \rangle |\langle \vec{u} \rangle|$$

λf total frontal area per unit ground area, (1-β)=fractional volume of the cell occupied by air, C_d=1.

Parameterization of the turbulent fluxes in the UCL

Coceal and Belcher, 2004

$$\left\langle \overline{u_i' u_j'} \right\rangle = -2 l_m^2 |S| S_{ij}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right)$$

$$|S| = \left(2 S_{ij} S_{ij}\right)^{1/2}$$

l_m is a spatially averaged turbulence integral length scale, estimated as

$$\frac{1}{l_m} = \frac{1}{kz} + \frac{1}{l_c}$$

And l_c is deduced imposing that at the top of the canopy h

$$\frac{1}{kh} + \frac{1}{l_c} = \frac{1}{k(h-d)}$$

With d displacement height

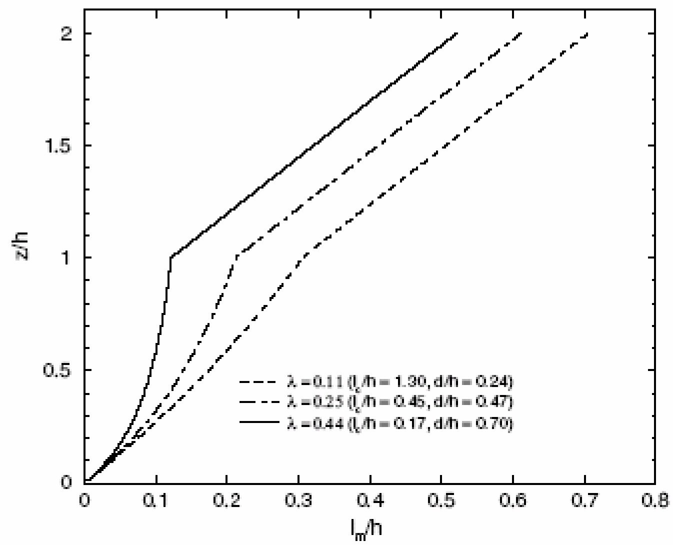
$$\frac{d}{h} = 1 + A^{-\lambda_p}\left(\lambda_p - 1\right)$$

λ_p Plan area density

From Coceal and Belcher, 2004

Length scale

O. COCEAL and S. E. BELCHER



e 3. Mixing-length profiles employed in the urban canopy model for different values of the obstacle density λ. Also shown are values of l_c/h, the size of the limiting constant eddy viscosity.

Wind speed

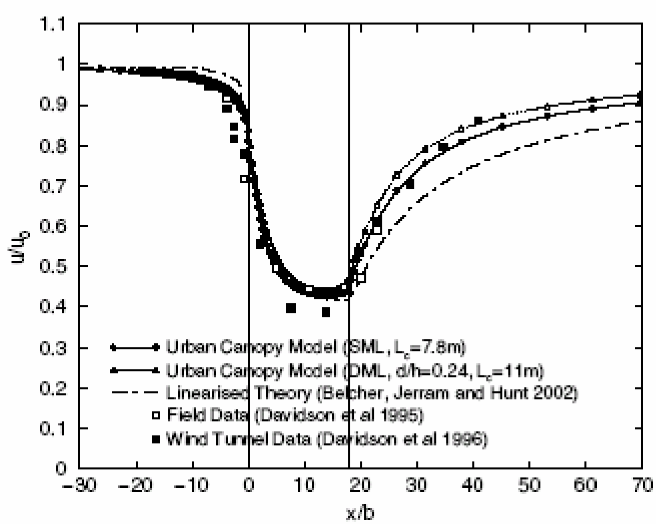


Figure 13. Deceleration of mean wind at half the roughness element height through canopy of roughness elements. Comparison of the urban canopy model with the measurements of Davidson *et al.* (1995, 1996). The canopy lies between $x/b = 0$ and 18; b is defined in Fig. 12.

Another approach is to solve a TKE budget and then estimate the turbulent exchange coefficients from TKE.

To do this, an extra term must be added in the TKE eqn. (it can be derived with similar arguments as it was done for momentum).

$$\frac{\partial \rho E}{\partial t} = -\frac{\partial \rho U_i E}{\partial x_i} - \frac{\partial \rho \overline{ew}}{\partial z} + \rho K_z \left[\left(\frac{\partial U_x}{\partial z} \right)^2 + \left(\frac{\partial U_y}{\partial z} \right)^2 \right] - \frac{g}{\theta_o} \rho K_z \frac{\partial \theta}{\partial z} - \varepsilon + D_E$$

Uno et al., 1989

$$\rho C_d \eta a(z) \left(\left| \langle u_1 \rangle \right|^3 + \left| \langle u_2 \rangle \right|^3 \right)$$

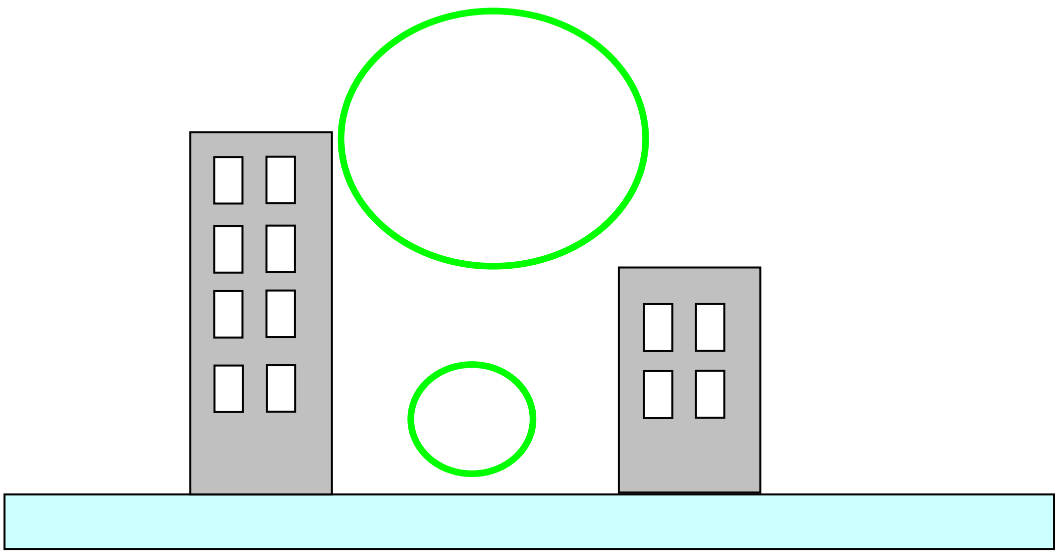
Brown and Williams, 1998

$$D_E = \rho f_{roof} C_d a(z) \sum_i \left| \langle u_i \rangle \right|^3$$

Martilli et al. 2002,

$$D_E = \rho C_{drag} \left| U_{IU}^{ort} \right|^3 \frac{S^V{}_{IU}}{V_{IU} - V_{IUbuild}}$$

The physical meaning of the term is to accelerate the transfer of energy from mean to turbulent motions (or from large to small scales).



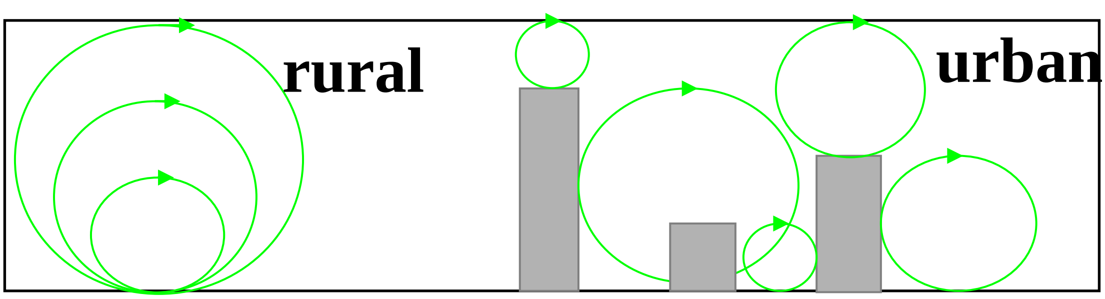
Buildings are very efficients in breaking large eddies in smaller ones.

In a K-l turbulence closure (one of the most used in mesoscale models), the dissipation and the diffusion coefficents are estimated using a length scale.

$$\frac{\partial \rho E}{\partial t} = -\frac{\partial \rho U_i E}{\partial x_i} - \frac{\partial \rho \overline{ew}}{\partial z} + \rho K_z \left[\left(\frac{\partial U_x}{\partial z} \right)^2 + \left(\frac{\partial U_y}{\partial z} \right)^2 \right] - \frac{g}{\theta_o} \rho K_z \frac{\partial \theta}{\partial z}$$

$$- \rho C_\varepsilon \frac{E^{3/2}}{l_\varepsilon} + D_E \qquad K_z = C_k l_k E^{1/2} \qquad \langle \overline{u'w'} \rangle = -K_z \frac{\partial U}{\partial z}$$

In rural area the length scale is proportional to the height above ground. Martilli et al. 2002 proposed two modifications for urban areas.



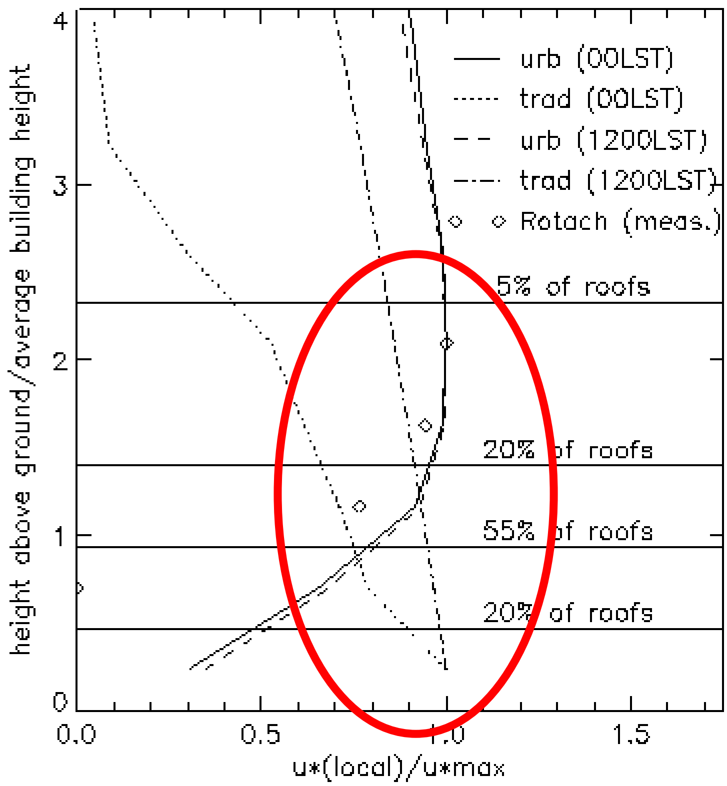
$$\left.\frac{1}{l_b}\right|_I = \sum_{iu=ibu}^{nu} \gamma(z_{iu}) \frac{1}{z_{iu}} \qquad \frac{1}{l} = \frac{1}{l_{old}} + \frac{1}{l_b}$$

$$\left. l_{ground} \right|_I = \frac{1}{\frac{W}{B+W} \frac{1}{z_I} + \frac{B}{B+W} \sum_{iu=1}^{iub-1} \gamma(z_{iu}) \frac{1}{z_I - z_{iu}}}$$

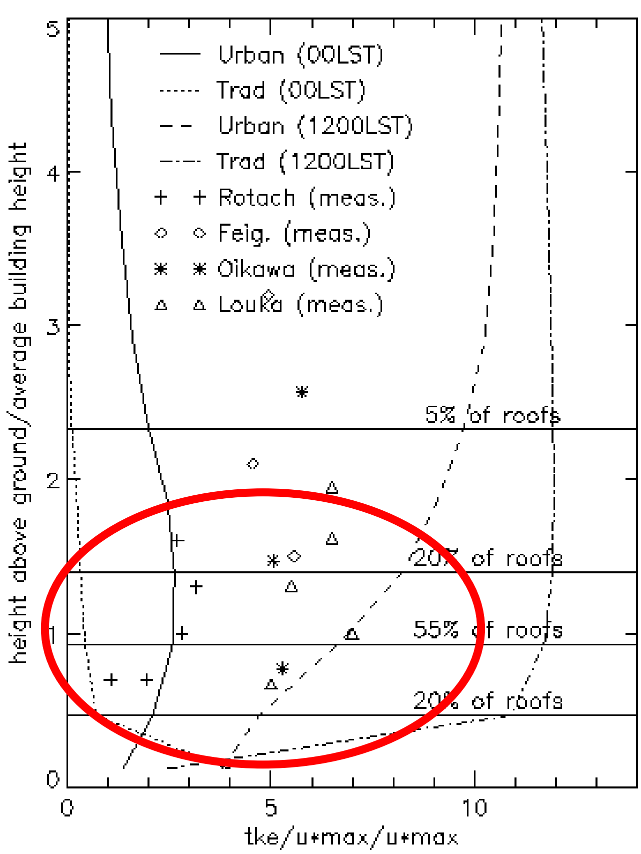
Modification of length scales

Reynolds Stress

From Martilli et al. 2002

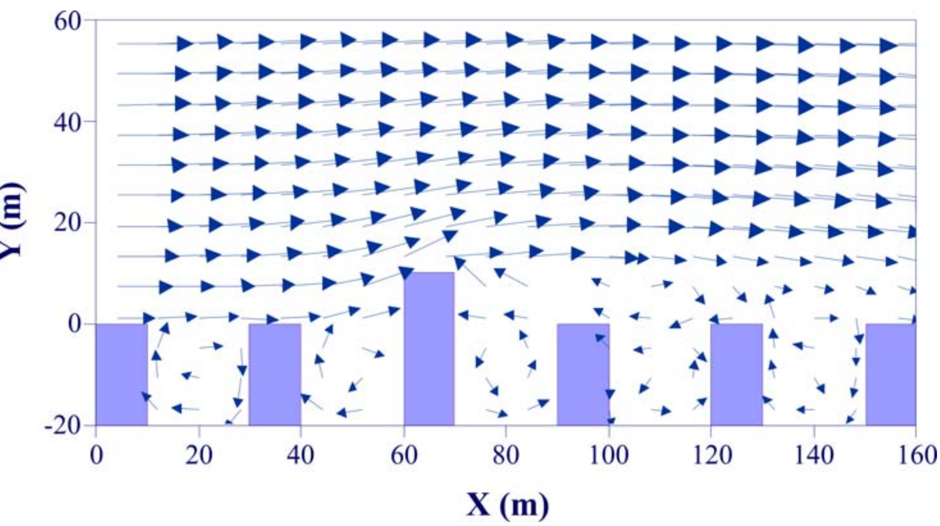


TKE



How to improve ?

Use street canyon CFD models to derive properties of the mean flow and parameterizations for mesoscale models.

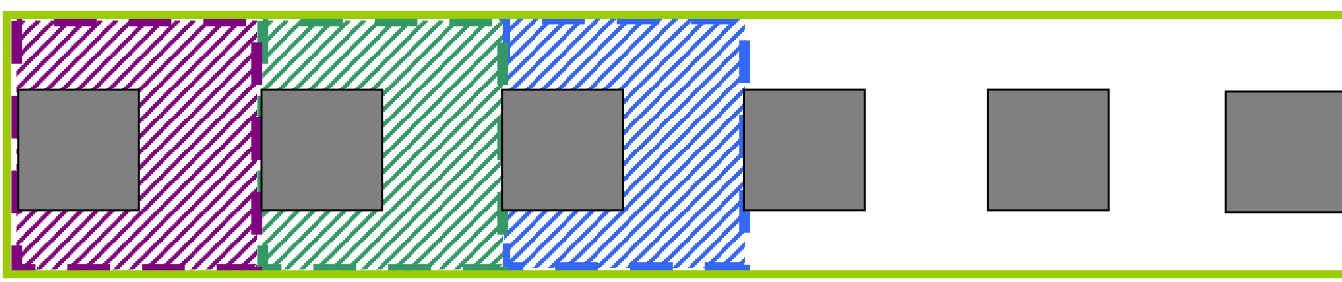


Buildings are explicitly resolved. Simulation at high resolution, but for very small domain.

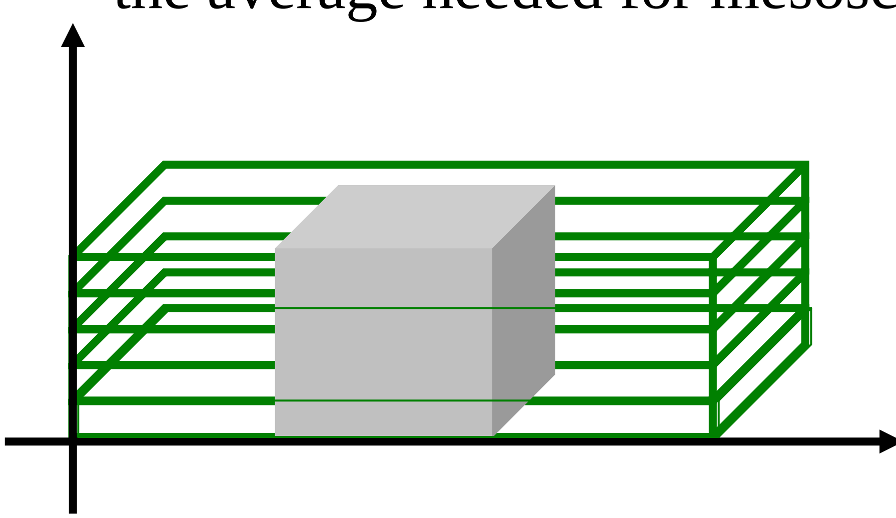
Figure 1. 2D and 3D building arrays in the USEPA meteorological wind tunnel.

CFD models validated against wind tunnel data.

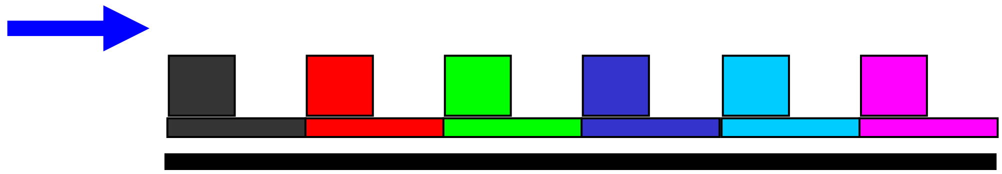
CFD simulation with model FLUENT of flow over an array of obstacles. Reproduction of wind tunnel experiment of M. Brown at U.S. EPA. (For more about the results, see Jose Luis Santiago's presentation).



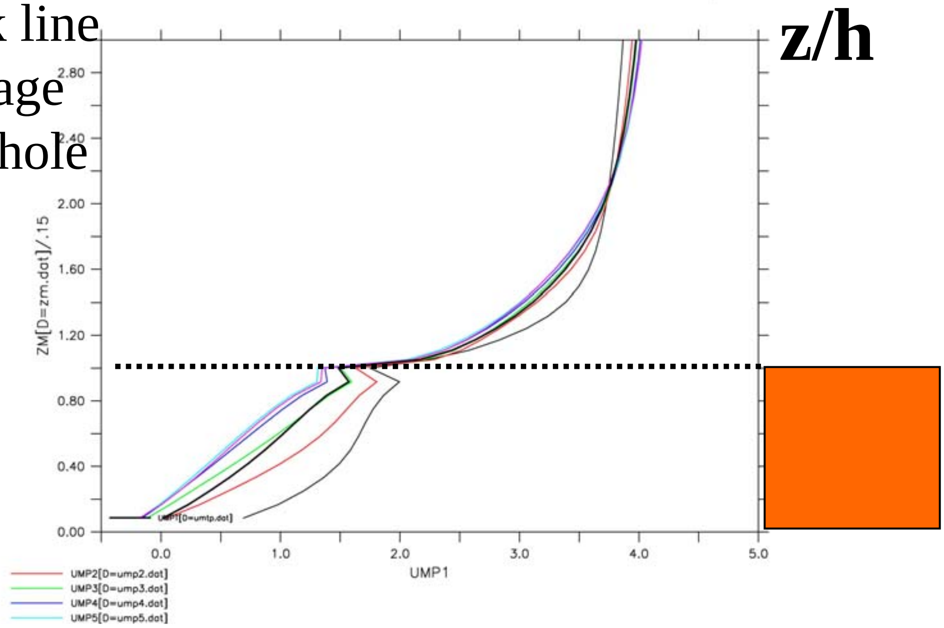
Spatial average of the results over thin slices of building-canyon units, and over the whole array. These is the closest to the average needed for mesoscale models.



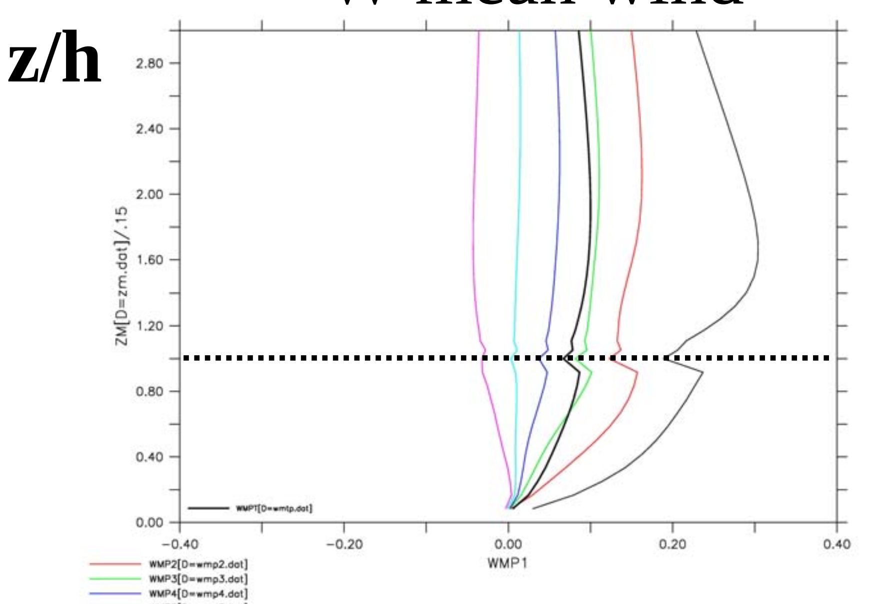
The color of the canyons corresponds to the color of the lines in the plots. The thick black line is the average over the whole array



U mean wind

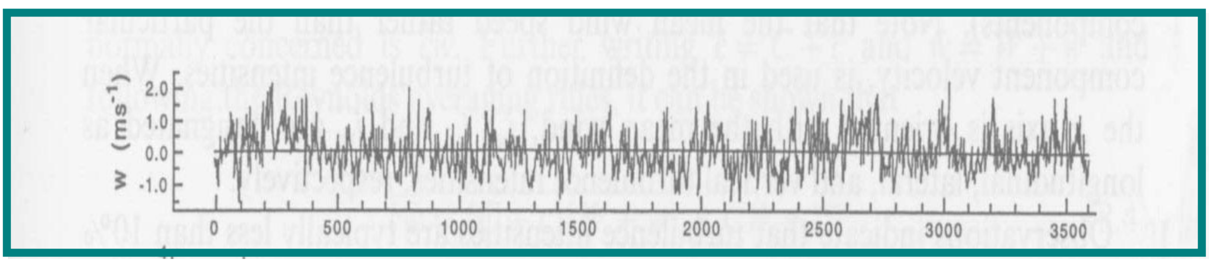


W mean wind



Turbulent fluxes

CFD model gives stationary solutions comparables with wind tunnel data. In which sense are the results stationary?
What is stationary is a time average of the results. The average is performed over a time scale larger than the time scale of the turbulent motions.



The turbulent fluxes computed by the CFD model are locally time averaged turbulent fluxes

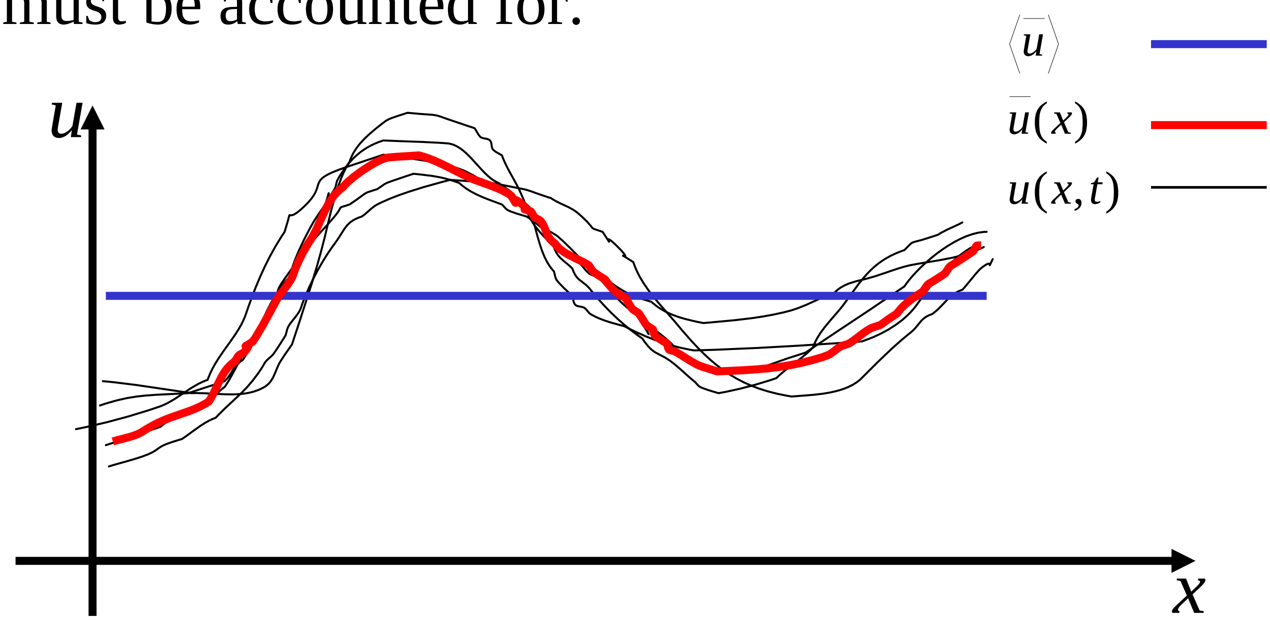
$$\overline{u'w'}(x) = \frac{1}{T}\int_T \left(u(x,t)-\bar{u}(x)\right)\left(w(x,t)-\bar{w}(x)\right)dt$$

$$\bar{u}(x) = \frac{1}{T}\int_T u(x,t)dt, \qquad \bar{w}(x) = \frac{1}{T}\int_T w(x,t)dt$$

CFD output

In reality they are also a space average over the grid cell, but since the grid cell of a CFD is very small, this is the most important part.

However, when the time and space average is made over a volume large enough (e. g. containing one or more street canyons), the subgrid fluxes arising from the spatial average must be accounted for.



To see it, it is useful to split the variable (e. g. wind speed) in three parts.

$$u(x,t) = \langle \bar{u} \rangle + \tilde{u}(x) + u'(x,t)$$

$$\tilde{u}(x) = \langle \bar{u} \rangle - \bar{u}(x)$$

$$u'(x,t) = u(x,t) - \langle \bar{u} \rangle - \bar{u}(x)$$

Brackets indicate the spatial average, and overbars the time average

$\tilde{u}$ is the spatial variation of the time mean flow around individual roughness elements

u' is the turbulent fluctuation (changing in time)

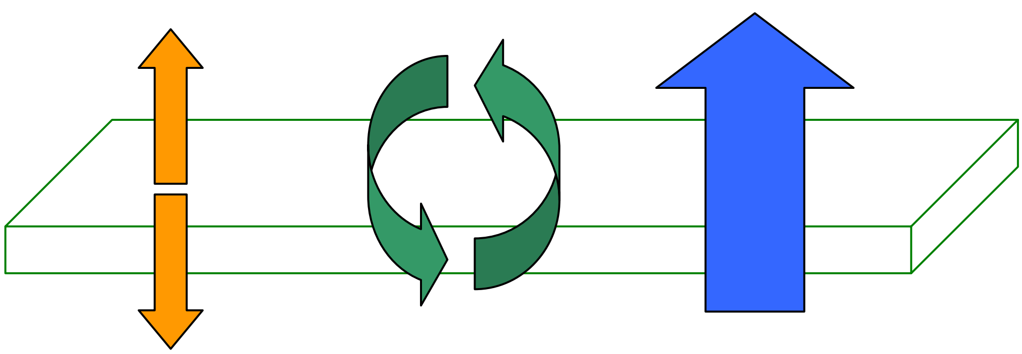
Averaging the momentum flux we have, then

$$\langle \overline{uw} \rangle = \langle \overline{u} \rangle \langle \overline{w} \rangle + \langle \overline{u'w'} \rangle + \langle \tilde{u}\tilde{w} \rangle$$

Resolved flux

Dispersive stress

Reynolds stress (turbulent)



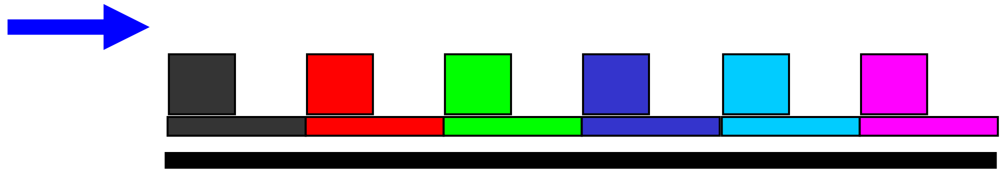
$\langle \overline{u'w'} \rangle$ $\qquad$ $\langle \tilde{u}\tilde{w} \rangle$ $\qquad$ $\langle \overline{u} \rangle \langle \overline{w} \rangle$

Time averaged structures smaller than the averaging scale

usually $\langle \overline{u'w'} \rangle >> \langle \tilde{u}\tilde{w} \rangle$

And the dispersive stress is neglected.

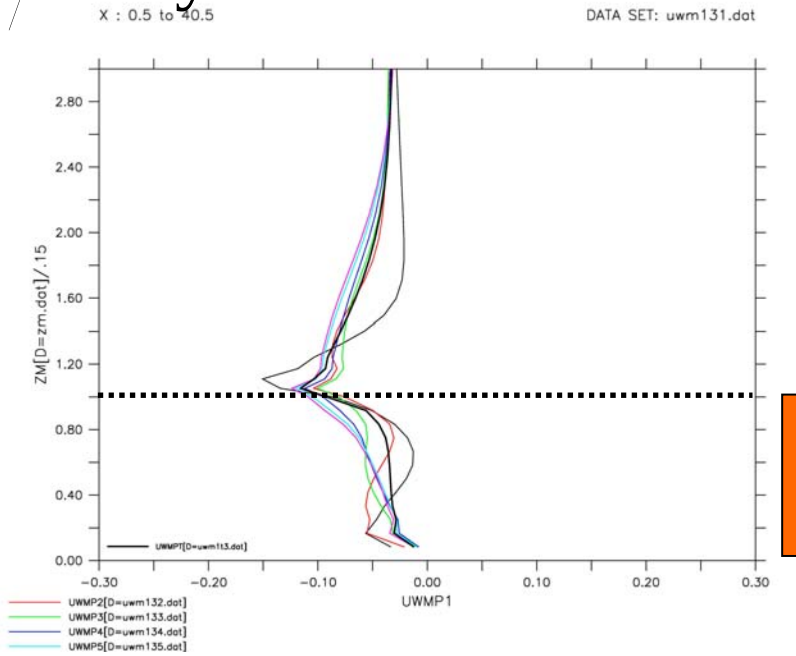
Is this the case for an urban canopy? We can estimate both terms from CFD results.

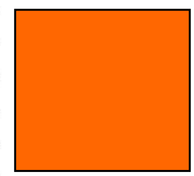


$\langle \overline{u'w'} \rangle$

Reynolds stress

z/h



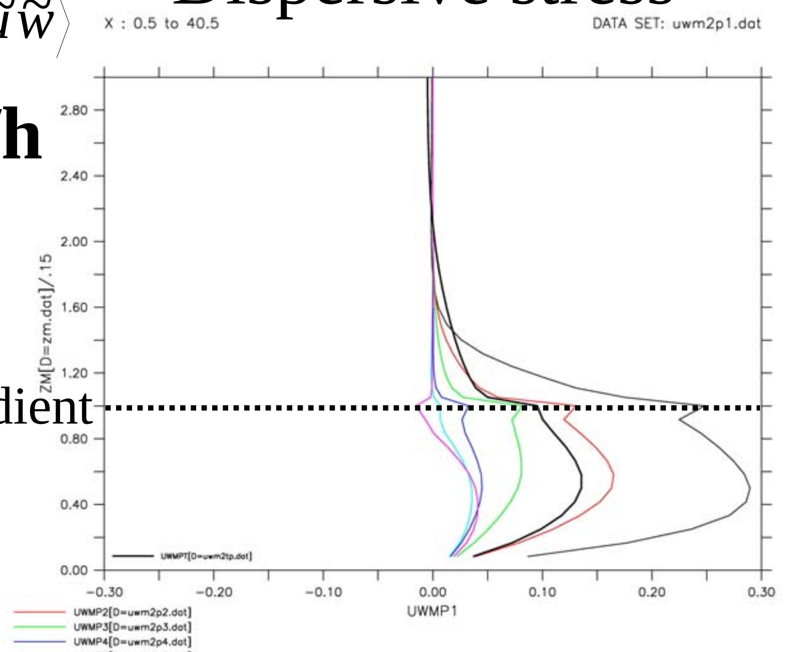


$\langle \tilde{u}\tilde{w} \rangle$

Dispersive stress

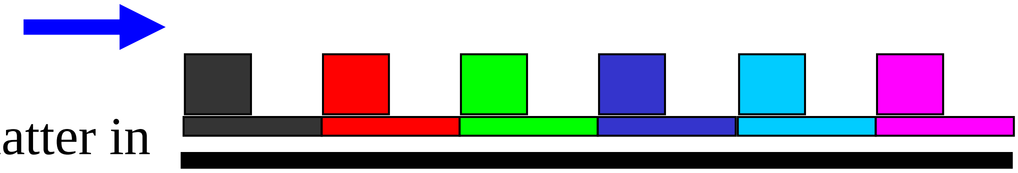
z/h

countergradient



Dispersive stress in the canopy is comparable, in magnitude, and opposite in sign to the Reynolds stress.

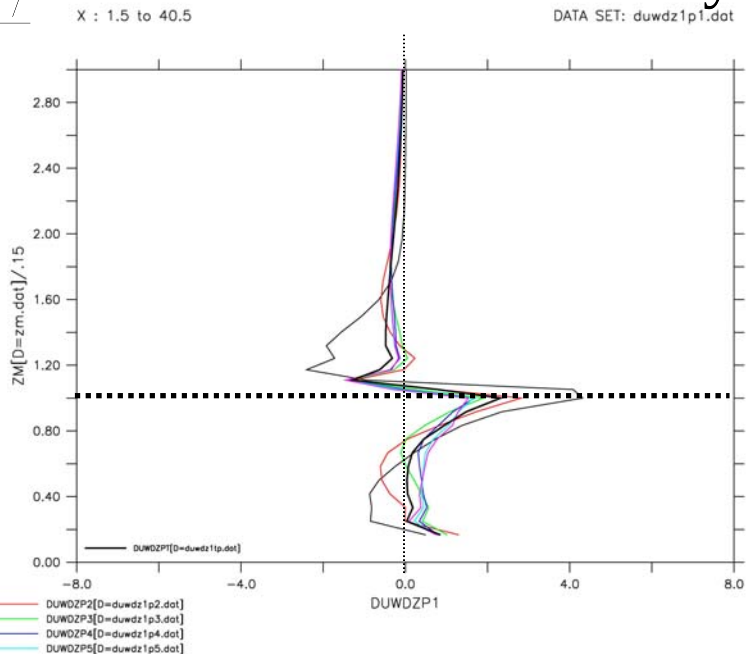
More important at city boundaries, less inside.

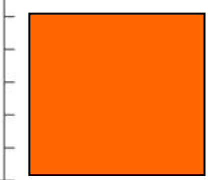


This is what matter in the momentum equation

$$-\frac{\partial \langle \overline{u'w'} \rangle}{\partial z}$$ Vertical derivative of Reynolds stress

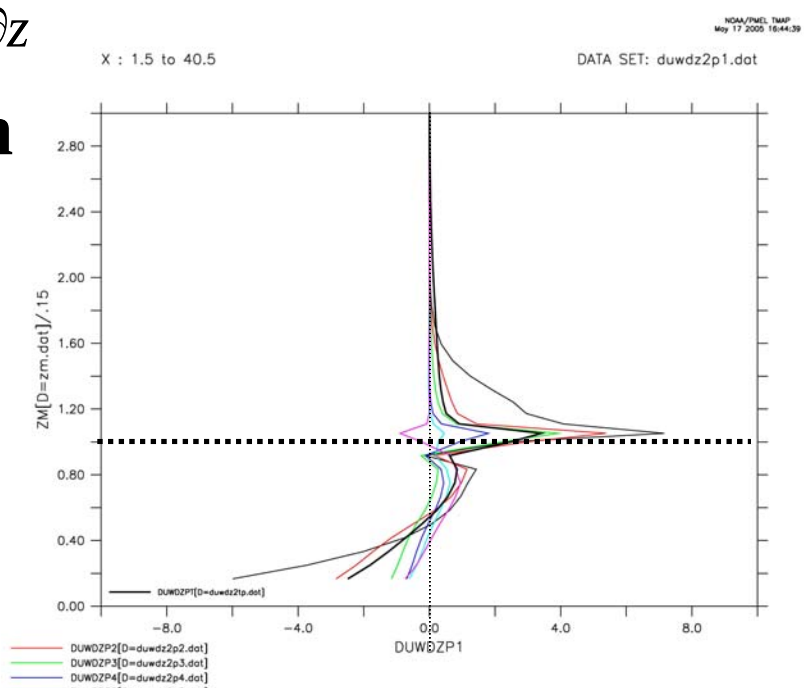
z/h



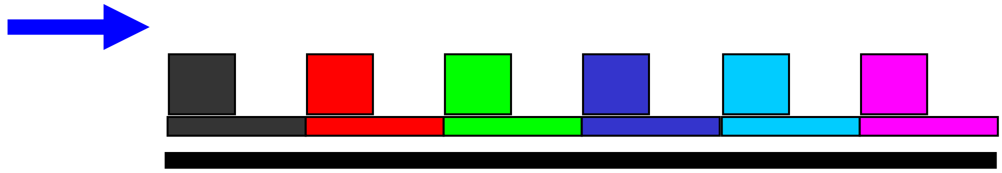


$$-\frac{\partial \langle \tilde{u}\tilde{w} \rangle}{\partial z}$$ Vertical derivative of Dispersive stress

z/h



Open question: how to parameterize the dispersive stress ?

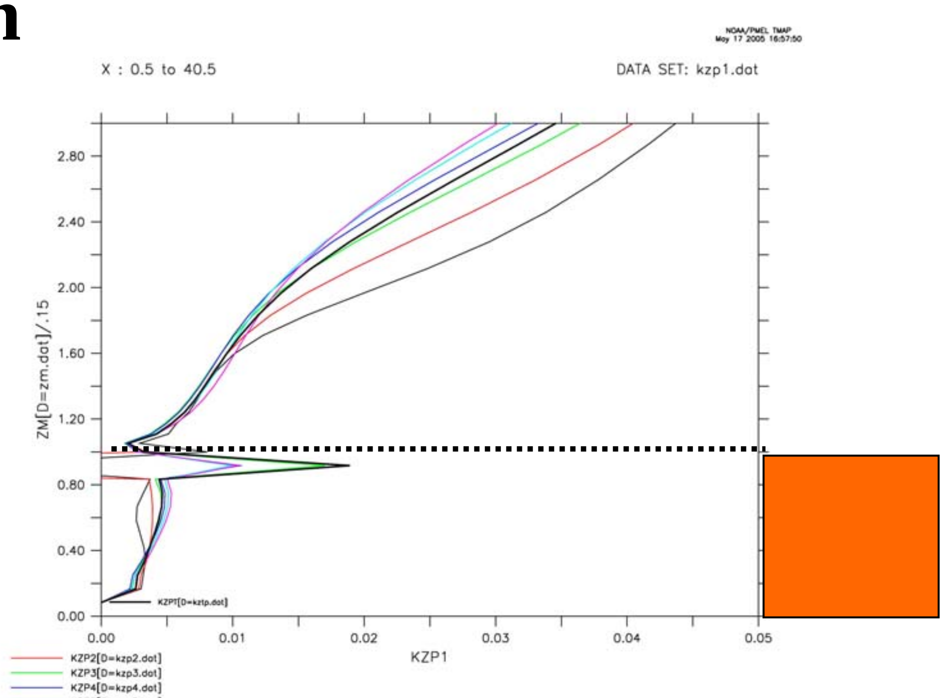


The most common way to parameterize the Reynolds stress is through an eddy diffusivity

$$K_z = -\frac{\langle \overline{u'w'} \rangle}{\dfrac{\partial \langle \overline{u} \rangle}{\partial z}}$$

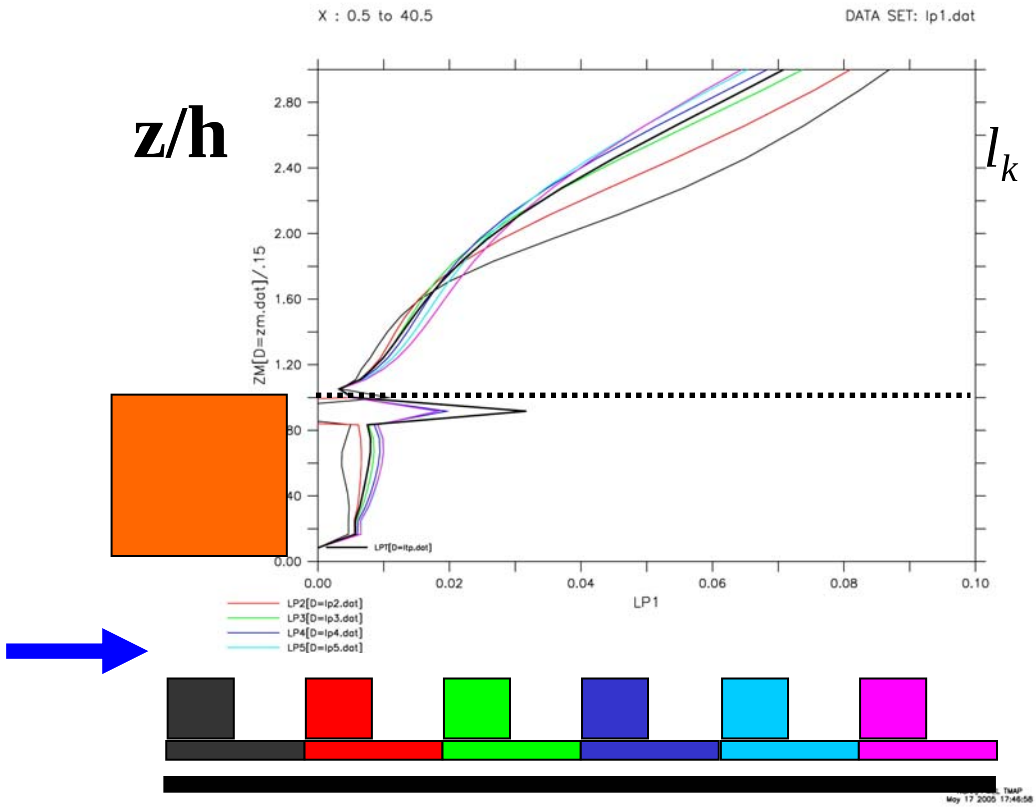
It is of interest to plot this ratio

z/h



When a TKE-l model is used, two length scales are needed to estimate the dissipation, and the eddy diffusivities. From the CFD data we can derive these two length scales.

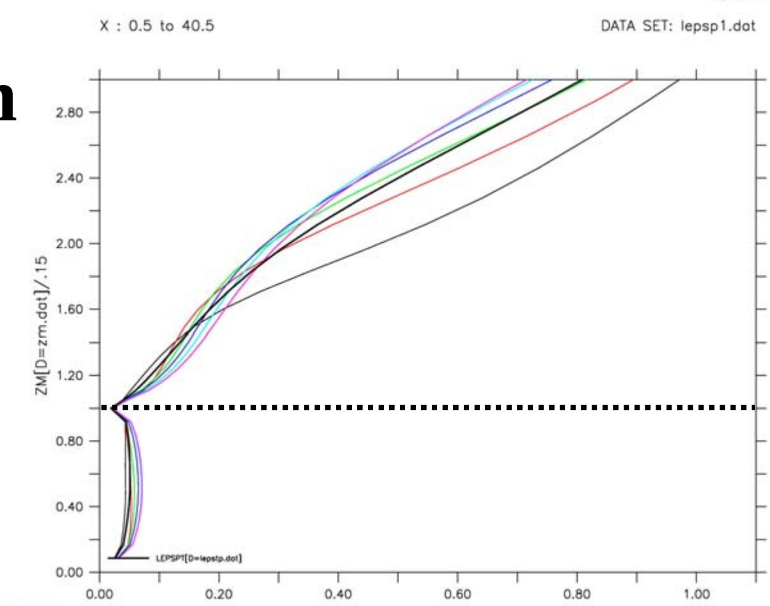
z/h



$$l_k = \frac{K_z}{\sqrt{\langle \overline{tke} \rangle}}$$

Length scale for eddy diffusivity

z/h



3 regions:
z/h<1
1<z/h<2
z/h>2

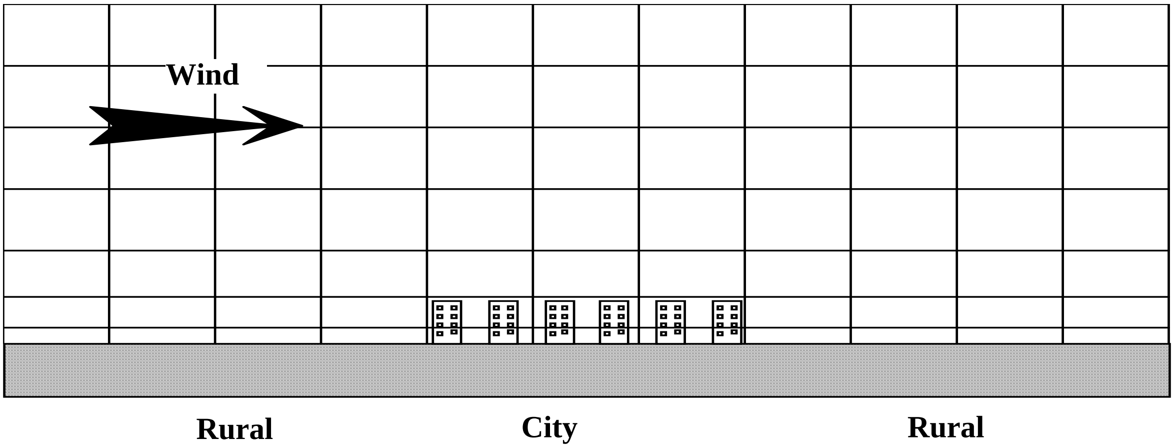
$$l_\varepsilon = \frac{\langle \overline{tke} \rangle^{3/2}}{\langle \overline{\varepsilon} \rangle}$$

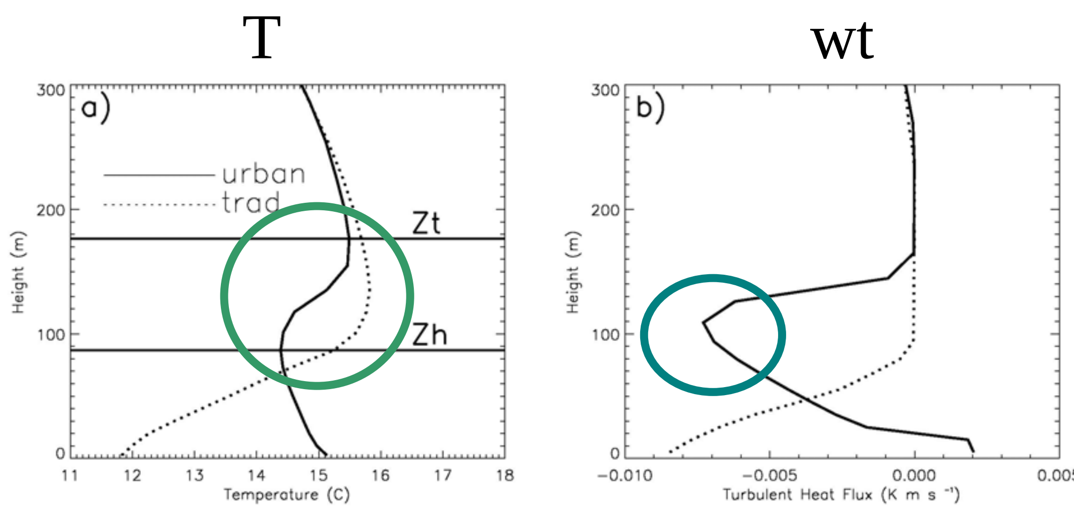
Length scale for dissipation

Is it possible to find a formula to represent them?

Test case

Wind speed 3/ms
Mean building height 15m



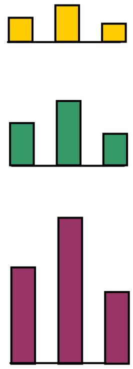


Sapporo (Uno et al. 1988) Z_h =40-60m, Z_t =90-100m

St. Louis (Godowitch et al. 1985) Z_h =150m, Z_t =325+/-105m

From Martilli, 2002

Building height and H/W ratio

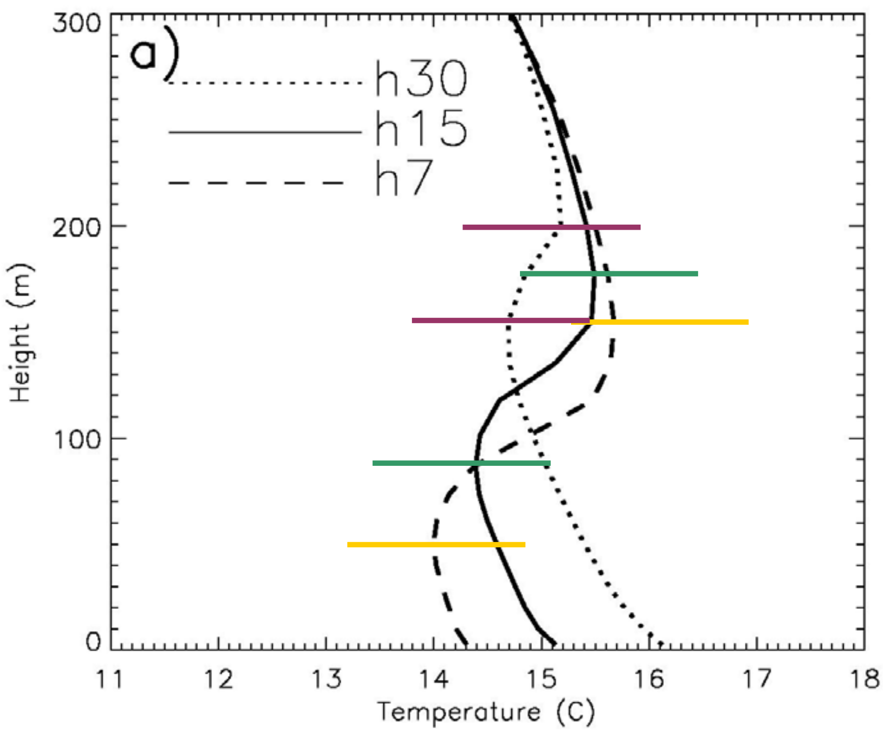


H=7.5m± 2.5 m

H=15m ± 5 m

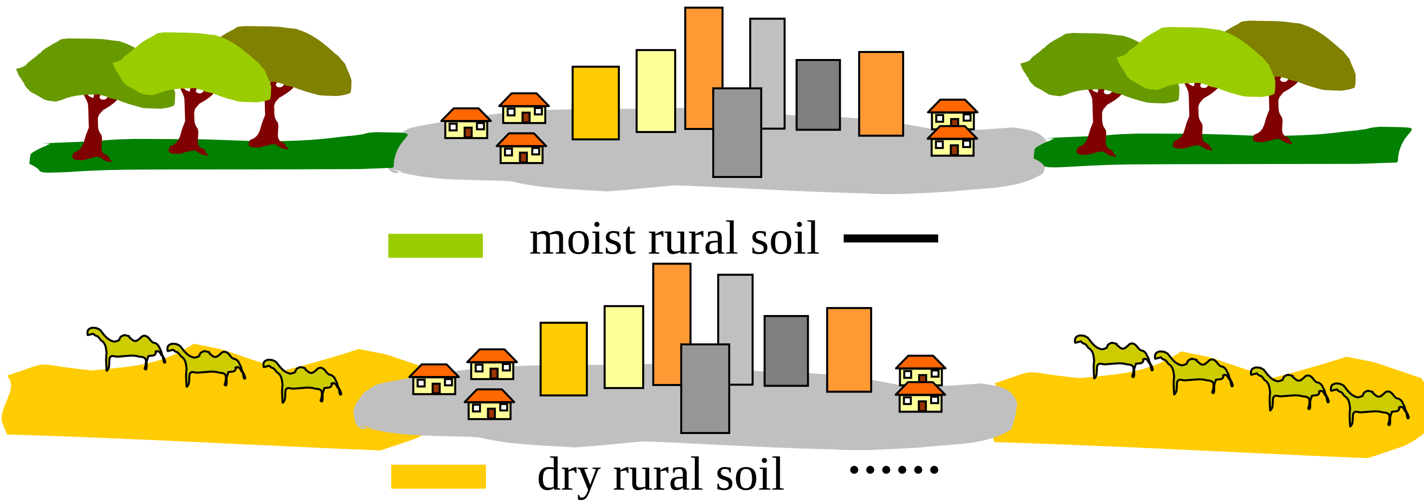
H=30m± 10 m

Temperature

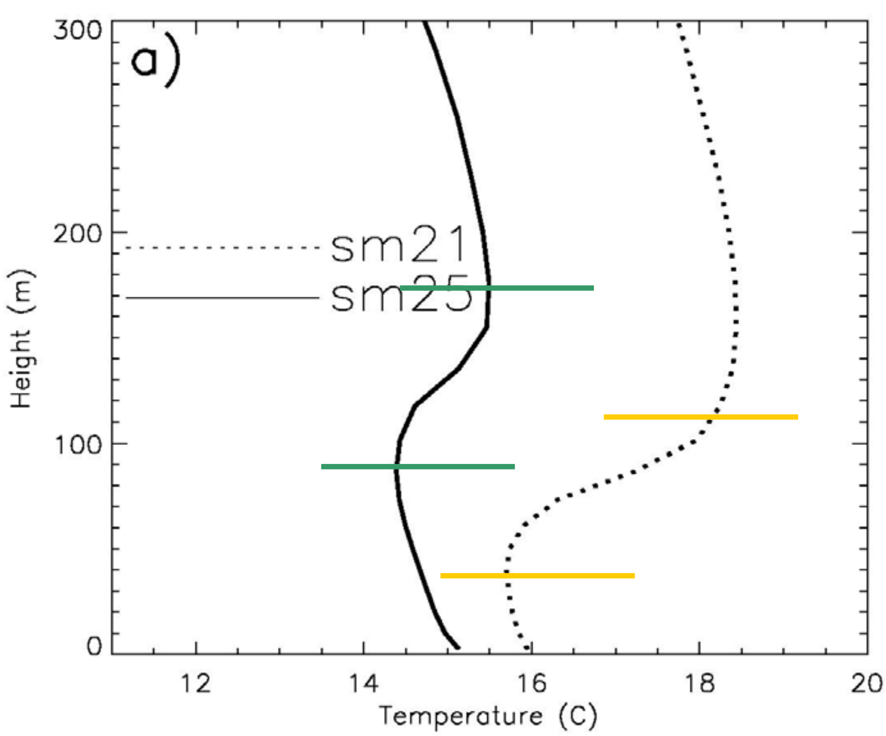


Night time

Rural soil moisture



Temperature

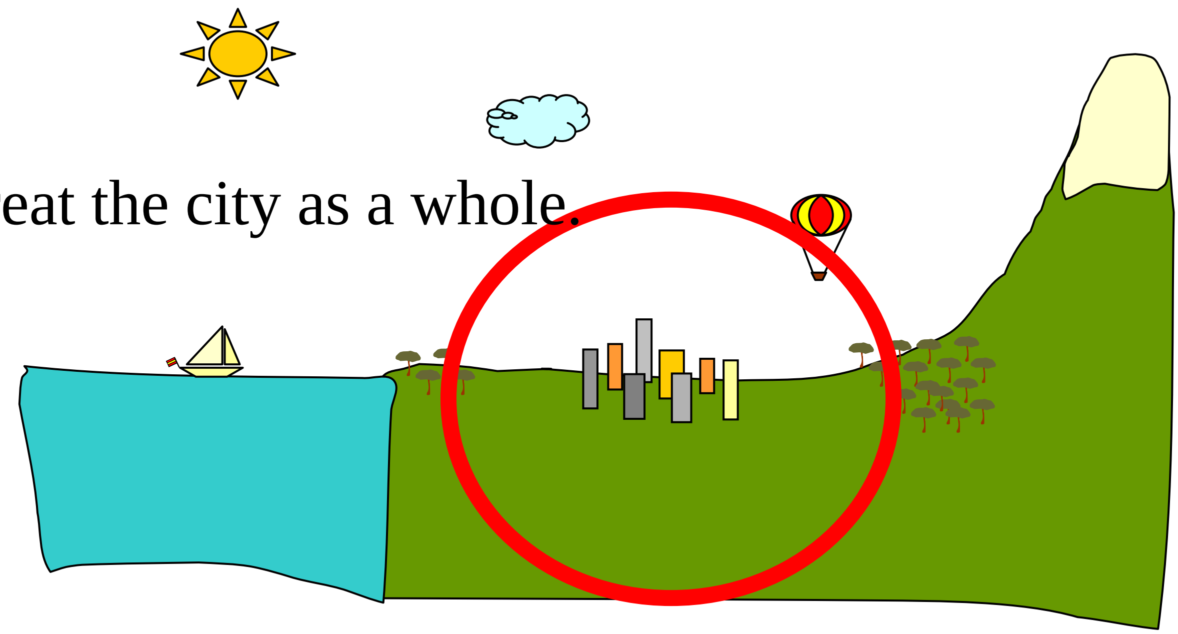


Night time

Conclusion

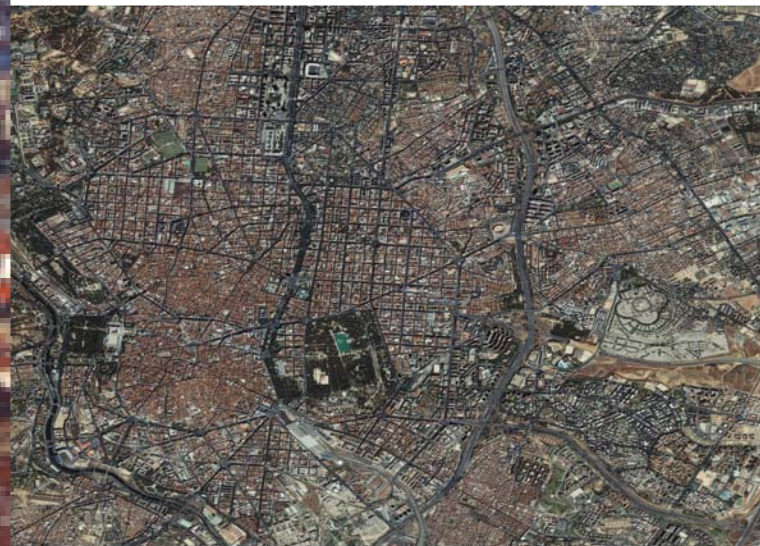
Today there is the knowledge and CPU power to make high resolution simulations of UCL and UBL, considering building energy, turbulent and sub-grid fluxes in the UCL.

Treat the city as a whole.

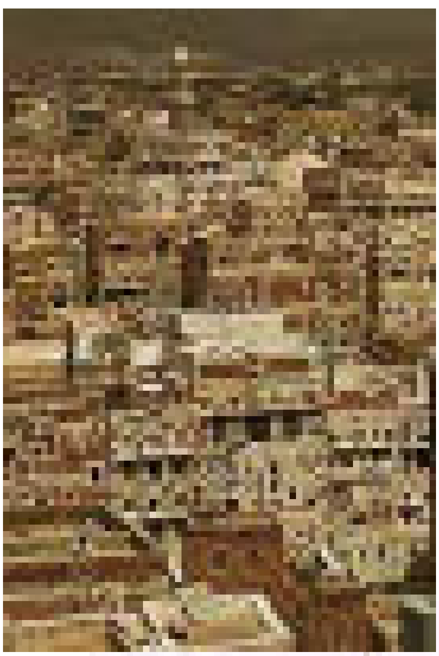


ONE numerical tool able to:

- Investigate UBL and UCL structure
- Estimate efficiency of air pollution abatement strategies
- Estimate efficiency of UHI mitigation strategies
- Account for cross interactions between these strategies



THE END



Thank you.