SAPIENZA
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High Resolution Numerical Modeling of an Idealized Daytime Urban Heat Island Circulation

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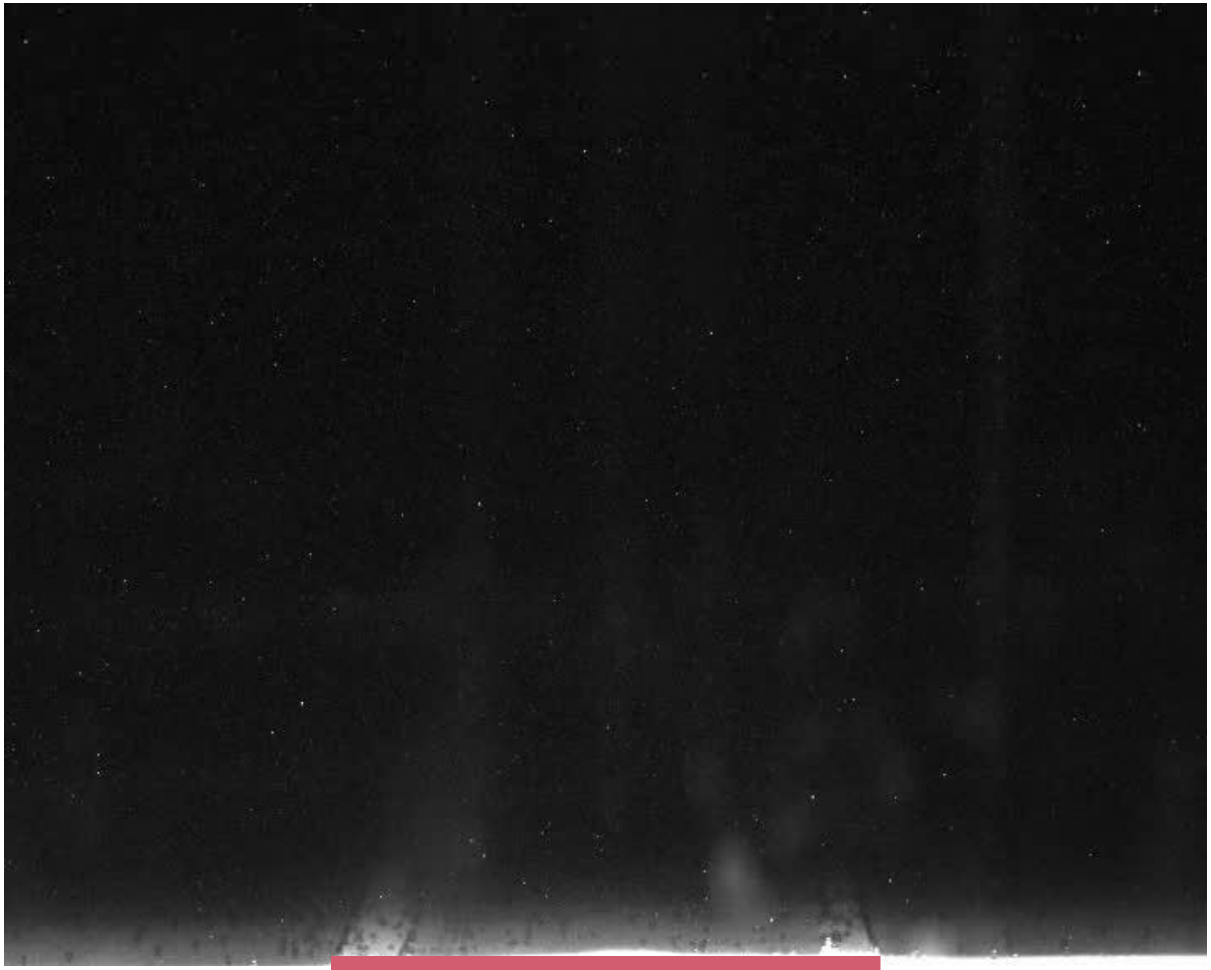
Urban Heat Islands: an introduction

- Atmospheric Boundary Layer
- In (urban and industrial) anthropic areas the temperature close to the ground is higher respect to the surrounding areas
- Definition: «The characteristic warmth of a town or city; it's due to human modifications of the surface and atmospheric properties which accompany urban development» (Oke 1995)

Urban Heat Islands: visualization



Electric resistance => UHI

Nocturnal case

$H_0 = 1.4\ 10^{-4}$ K m s^{-1}
N=0.43 s^{-1}

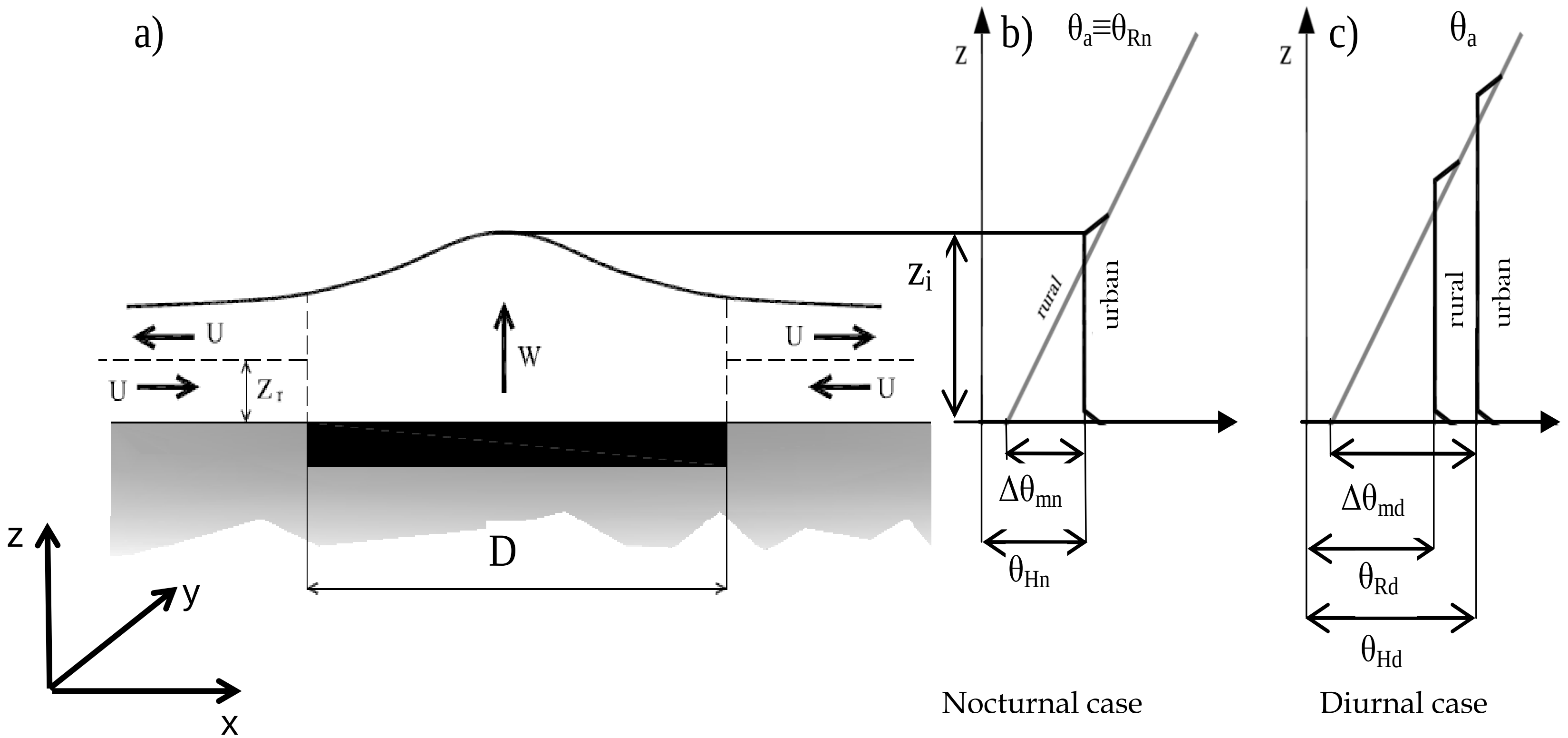
Urban Heat Islands: visualization

Electric resistance => UHI

Diurnal case

H_0= 1.4 10^{-4} K m s^{-1}
N=0.43 s^{-1}

Urban Heat Islands: a schematic representation



Urban Heat Islands: motivations

- Effects on local circulation and microclimate and, consequently, on the global climate (Mirzaei & Haghighai, 2010)
- Influence on the intensity and distribution of mesoscale phenomena (surface heat flux, momentum flux, moisture flux) (Ashley et al., 2012)
- Pollutants remain trapped within the dome (Hinkel et al., 2003, Akbari et al., 2001, Guhathakurta & Gober, 2010)
- Hydrologic cycle (Lin et al., 2011)
- Global warming (Chen et al., 2006)

Surface energy balance

(Deardorff 1978)

$$R_S\downarrow - R_S\uparrow + R_L\downarrow - R_L\uparrow - H_{sg} - H_e = Q_G$$

$$(1-\alpha_r)R_S\downarrow + R_L\downarrow - \varepsilon_g\sigma T_g^4 - H_{sg} - H_e = Q_G$$

$$(1-\alpha_u)R_S\downarrow + R_L\downarrow - \varepsilon_u\sigma T_u^4 - H_{sg} - H_e + Q_f = Q_G$$

- Reduced albedo of an urban area respect to a rural area
- Effect of thermal sources
  - Urban areas: cars, heating, conditioning systems
  - Industrial areas: industrial processes with a high energetic consumption (steel mills, oil plants)

$R_S\downarrow$ down-coming short wave radiative flux

$R_L\downarrow$ down-coming long wave radiative flux

H_{sg} sensible heat flux at the ground toward the atmosphere

H_e latent heat flux

Q_G soil heat flux

ε_g emissivity of the ground surface in the infrared region of wavelength

σ Stefan-Boltzmann constant

T Temperature

Q_f Anthropogenic heat flux

Similarity theory for small ratio UHIs

(z_i/D<<1)

- Parameters describing the UHI phenomenon: D, $\sqrt{g\beta\frac{\partial\theta_a}{\partial z}}$, H_0
- Numerical results normalized by similarity theory scaling parameters (bulk model of Lu et al., 1997)
- Scale quantities:
  - horizontal velocity scale $u_L = (g\beta H_0 D)^{1/3}$
  - vertical velocity scale $w_L = u_L^2 / ND$
  - UHI intensity (or temperature macroscale) $\Delta\theta_m$
  - convective temperature microscale $\theta_L = g\beta/(w_L N)$
  - timescale D/w_L

Numerical model

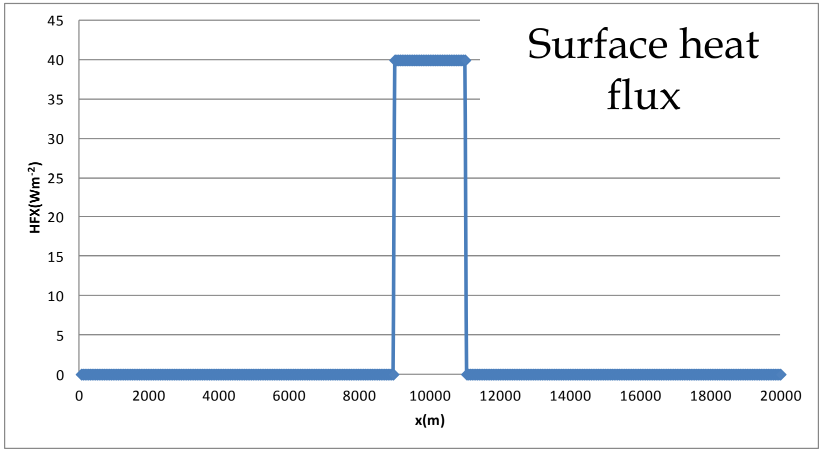
- Large Eddy Simulations with WRF (Weather Research and Forecast):
  - 3D, non stationary, non hydrostatic, compressible model
  - staggered Arakawa C-type grid
  - terrain-following hydrostatic-pressure vertical coordinate
  - $\Delta x = \Delta y = 50$ m
  - vertical stretching ($\Delta z \approx 2$ m close to the ground up to 90 m at higher heights)
  - parametric schemes for describing the phenomenon physics

Numerical set-up

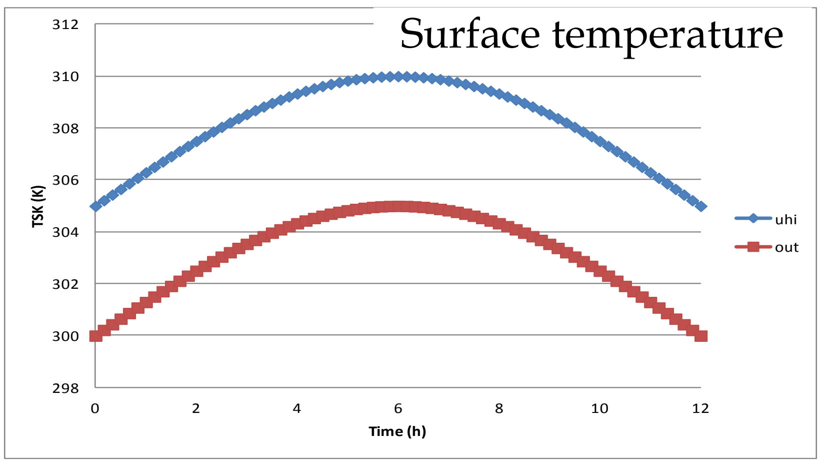
- Simulation of the UHI in idealized conditions:
  - Simplified geometry
  - Periodic boundary conditions
  - Dry atmosphere
  - No other local winds

- A modified subgrid-scale (SGS) model with a prognostic equation for the SGS turbulent kinetic energy (TKE) is introduced to take into account the effects of the anisotropy of the grid

Ground thermal forcing (1)



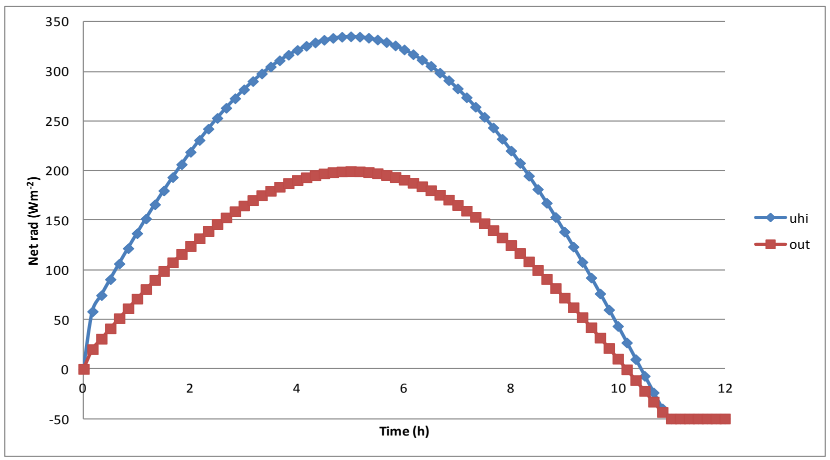
The surface heat flux is directly imposed in the thermal energy equation



A more realistic forcing is then employed by imposing a sinusoidal time dependence for the surface temperature anomaly and using a surface layer parameterization based on the Monin-Obuchov similarity theory to compute the surface heat flux and the friction velocity necessary to drive the first layer of the grid.

Ground thermal forcing (2)

Radiation at the ground



The third kind of forcing used to simulate the UHI is the radiative forcing. The same value of the radiative flux is imposed on the entire domain and different reflective and thermal properties of the surface are imposed to reproduce the different thermal behavior of the urban and the rural areas.

In this case both the surface model based on the Monin-Obukhov similarity theory and the 5-layers land surface scheme are used.

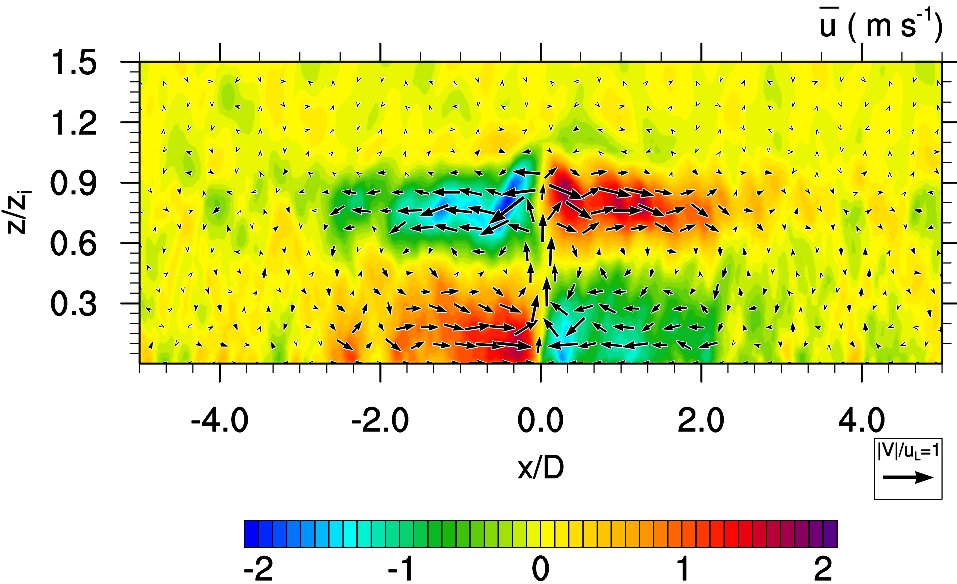
Numerical simulations: parameters

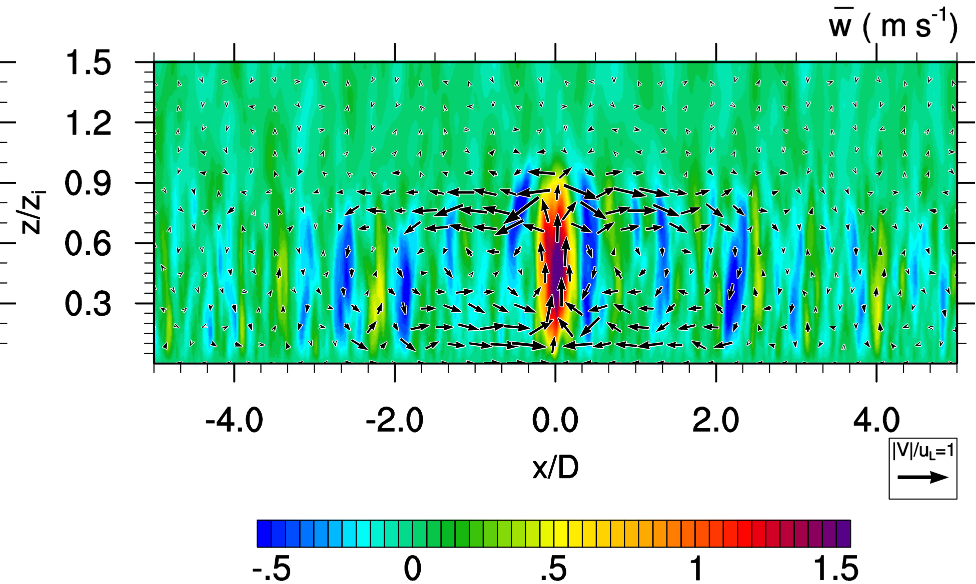
	N_x, N_y, N_z	UHI width D (m)	Ground heat Forcing	UHI forcing	Brunt-Väisälä frequency N (s^{-1})
Sim 1	200x100x58	2000	-	H_0 = 0.03 K m s^{-1}	0.0128
Sim 2	400x100x58	2000	-	H_0 = 0.03 K m s^{-1}	0.0128
Sim 3	400x100x58	2000	Sinusoidal: $\Delta\theta_{s,max}$ = 5 K	$\Delta\theta_m$ = 5 K	0.0128
Sim 4	400x100x58	4000	Sinusoidal: $\Delta\theta_{s,max}$ = 5 K	$\Delta\theta_m$ = 5 K	0.0128
Sim 5	400x100x58	4000	Sinusoidal: $\Delta\theta_{s,max}$ = 5 K	$\Delta\theta_m$ = 5 K	0.0256

N_x, N_y, N_z		400x100x58
UHI width D (m)		2000
Surface heat forcing (W m^{-2})	U	R_S= 450
	R	R_L*= -50
Brunt-Vaisala frequency N (s^{-1})		0.0128

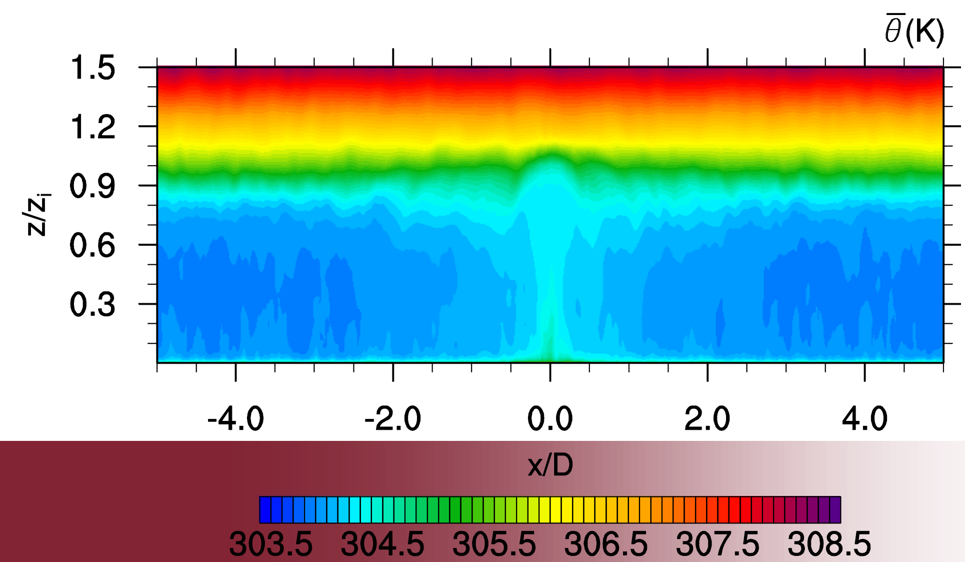
	v_g (ms^{-1})	Roughness z_0		Albedo		Thermal Inertia		Anthropogenic heat
		U	R	U	R	U	R	
Sim 6	No	0.1		0.15	0.45	0.05	0.03	No
Sim 7	2	0.1		0.15	0.45	0.05	0.03	No
Sim 8	5	0.1		0.15	0.45	0.05	0.03	No
Sim 9	10	0.1		0.15	0.45	0.05	0.03	No
Sim 10	No	0.3	0.1	0.15	0.45	0.05	0.03	No
Sim 11	No	0.5	0.1	0.15	0.45	0.05	0.03	No
Sim 12	No	0.1		0.15	0.6	0.05	0.03	No
Sim 13	No	0.1		0.15	0.8	0.05	0.03	No
Sim 14	No	0.1		0.15	0.45	0.05	0.04	No
Sim 15	No	0.1		0.15	0.45	0.02	0.03	No
Sim 16	No	0.1		0.15	0.45	0.05	0.03	Yes
Sim 17	No	0.1		0.15	0.45	0.05	0.03	Yes

Numerical results: mean quantities

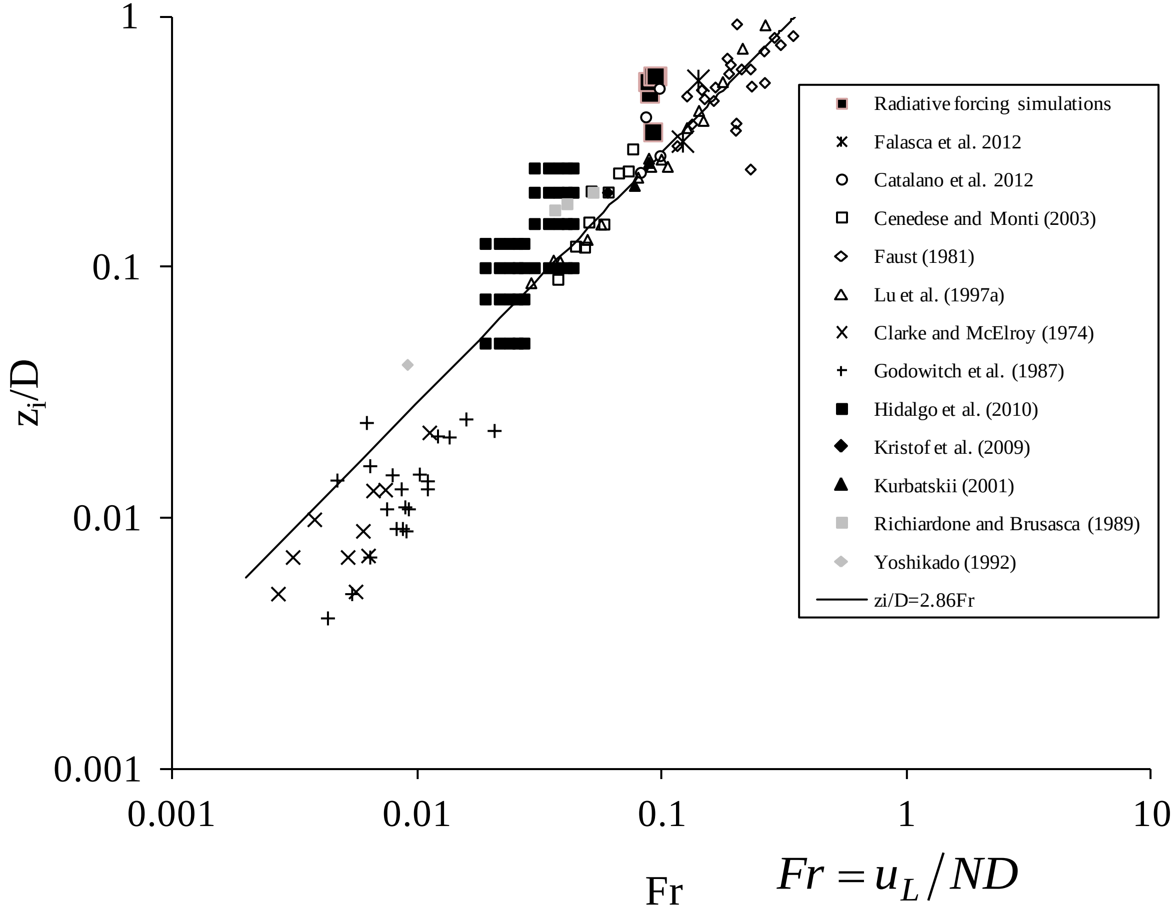




SIM 6

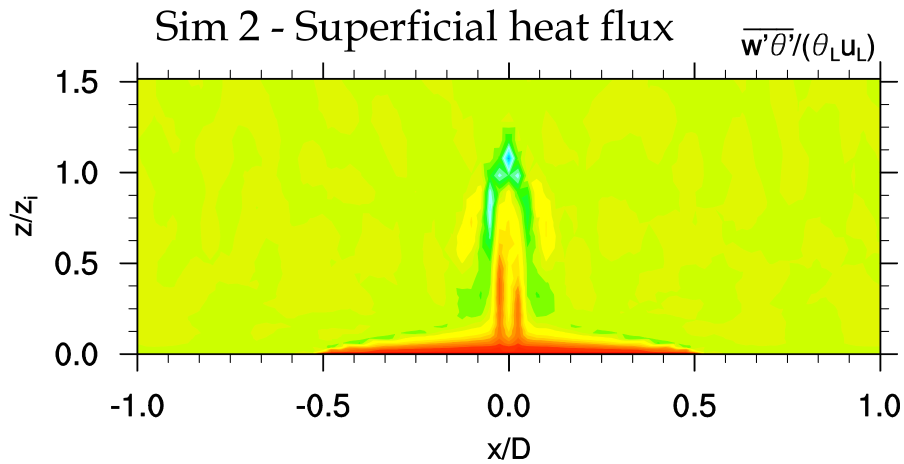


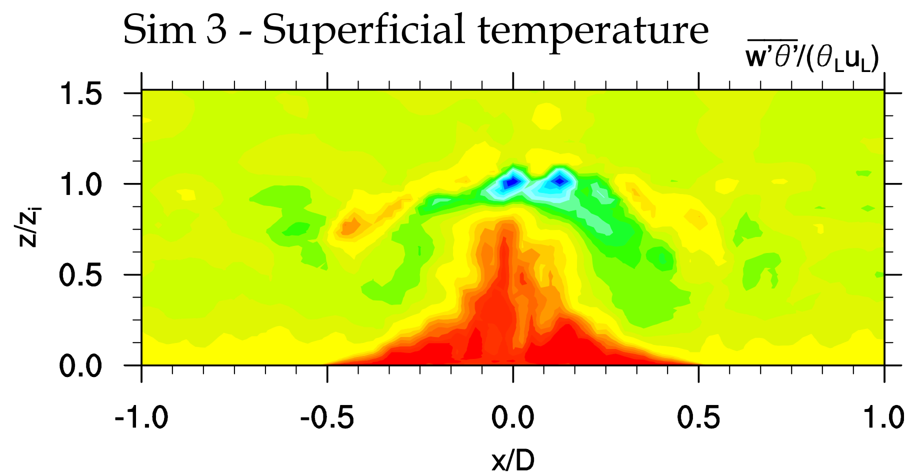
Comparison among numerical, experimental and field data

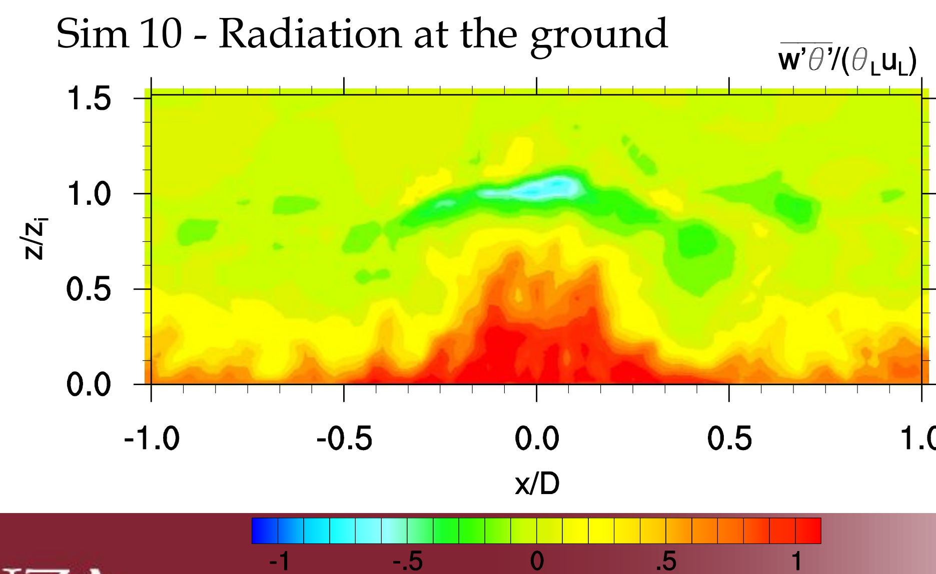


$$Fr = u_L / ND$$

Numerical results: effects of the forcing

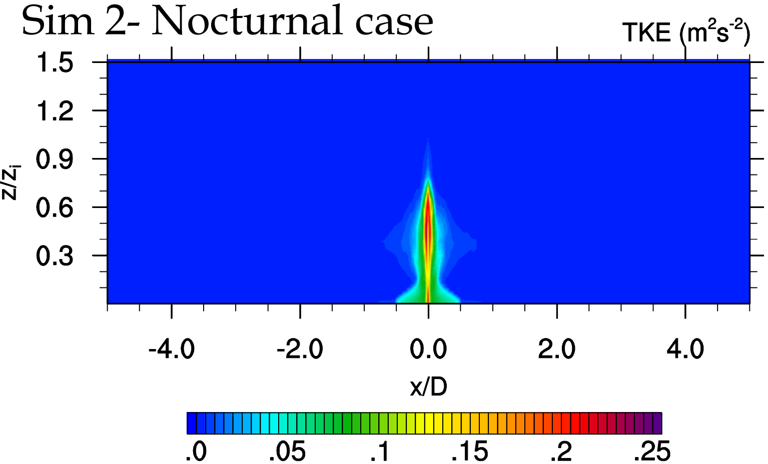




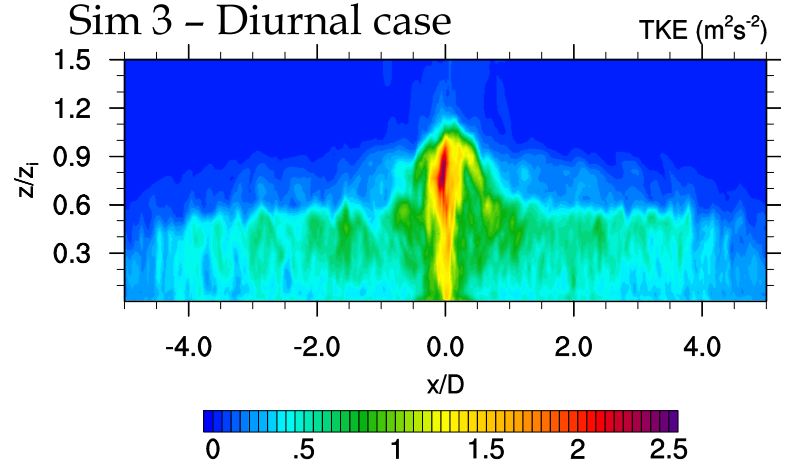


Numerical results: TKE

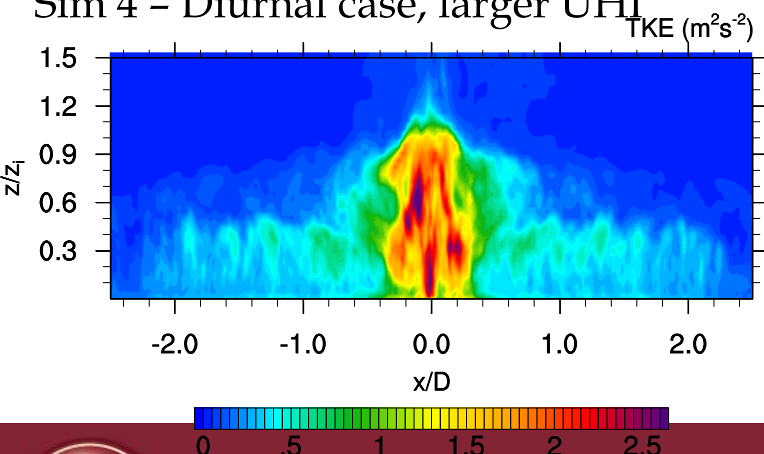
Sim 2- Nocturnal case



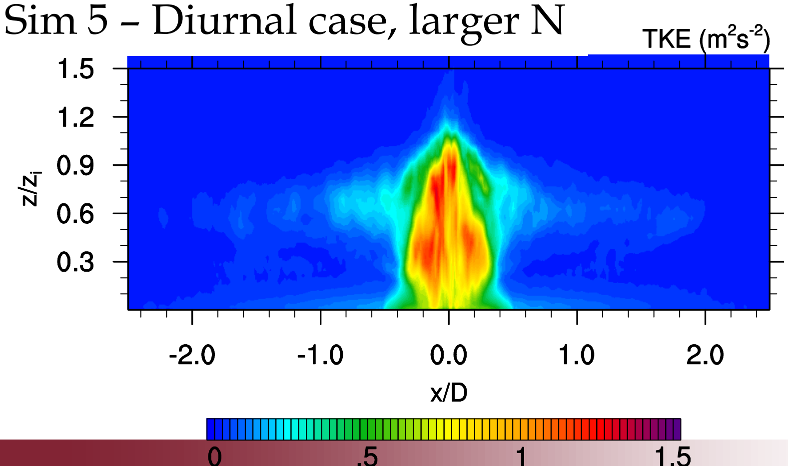
Sim 3 – Diurnal case



Sim 4 – Diurnal case, larger UHI

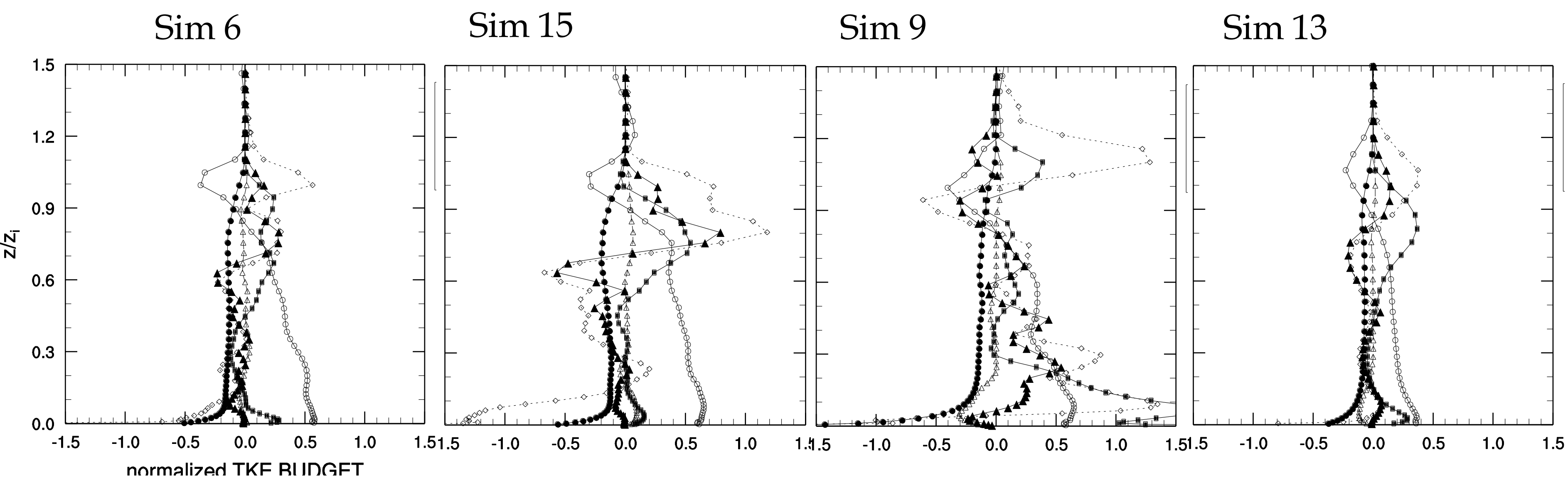


Sim 5 – Diurnal case, larger N



Numerical results: TKE budget

$$\frac{\partial TKE}{\partial t} = \underbrace{-\bar{u}\frac{\partial TKE}{\partial x}}_{adv\_h} \underbrace{-\bar{w}\frac{\partial TKE}{\partial z}}_{adv\_v} \underbrace{-\left(\overline{u'^2}\frac{\partial \bar{u}}{\partial x} + \overline{u'w'}\frac{\partial \bar{w}}{\partial x} + \overline{u'v'}\frac{\partial \bar{v}}{\partial x} + \overline{w'^2}\frac{\partial \bar{w}}{\partial z} + \overline{u'w'}\frac{\partial \bar{u}}{\partial z} + \overline{v'w'}\frac{\partial \bar{v}}{\partial z}\right)}_{Shear\ production} + \underbrace{\frac{g}{\theta}\overline{w'\theta'}}_{Buoyancy\ production} \underbrace{-\left(\frac{\partial}{\partial x}\overline{u'TKE} + \frac{\partial}{\partial z}\overline{w'TKE}\right)}_{Turbulent\ transport} - \varepsilon$$



In the lower part of the PBL the primary source of turbulence is the buoyancy up to z/z_i= 0.6 and the shear is important only near the surface. The dissipation term is nearly constant with height and balances the buoyancy at the bottom of the domain. The turbulent transport term is the main source of TKE at the PBL top and determines an important redistribution of TKE from the lower half of the PBL to the upper half of the PBL as observed by Moeng and Sullivan (Moeng and Sullivan 1994) for the convective PBL.

Conclusions (1)

- A significant inversion layer, associated to an intense entrainment over the urban site, has been evidenced
- This feature strongly affects the dispersion properties of the atmosphere
- The characteristic thermal structure of the UHI plays a fundamental role in the redistribution of heat fluxes to the larger scales and hence on the regional climate
- Validation of the relation between zi/D and the Froude number

Conclusions (2)

- Detailed analysis of the energy budget
- Detailed characterization of the PBL structure in terms of mean and turbulent fields