ON THERMAL STRATIFICATION IN REAL STREET CANYONS WITH TREES: CONSEQUENCES FOR LOCAL AIR QUALITY

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Introduction

City of Lecce

Without trees

With two-rows trees

Trees benefits

- Remove pollutants
- Release oxygen
- Offset communities' carbon footprint
- Reduce stormwater runoff
- Save energy
- Provide wildlife habitants
- Aesthetic benefit

positive

reduced pollutant concentration

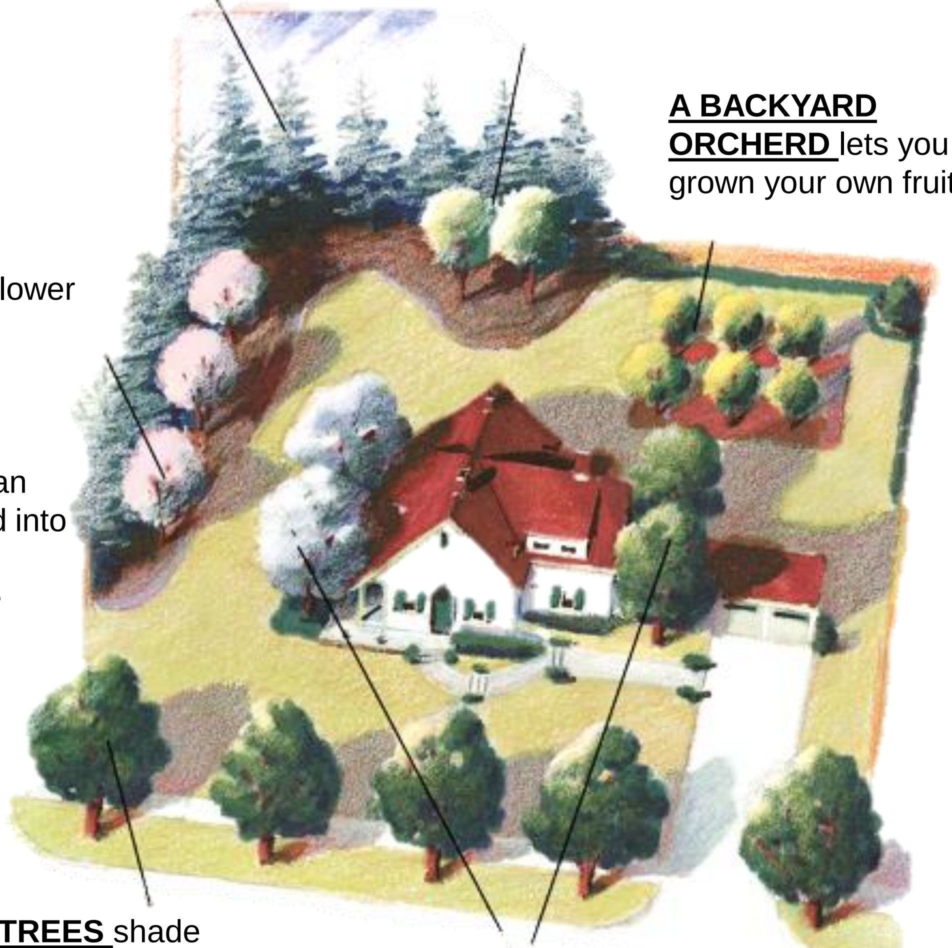
Trees disadvantages

- Buildings act as obstacle to air flow
- Reduced air exchange between canyon flow and roof-top
- Accumulation of traffic-related pollutants
- Placing of trees in street canyon can amplify pollutant concentrations at street level
- Less ventilation, reduced dispersion and dilution increase blockage on already restricted air flow

negative

increased pollutant concentration

Trees can **REMOVE CO_2** from the air, **PRODUCE OXYGEN**.



Objective

Role of vegetation in street canyons on local ventilation & city "breathability"

- To study how **urban vegetation** and **heat** release from buildings and other urban "components" affect ventilation conditions in street canyons

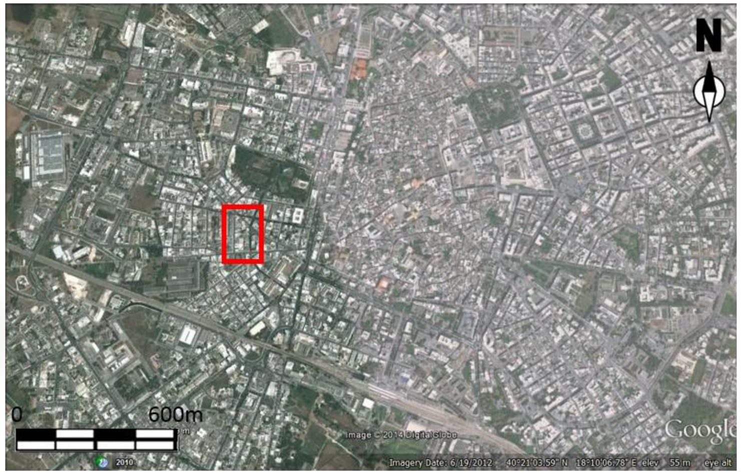
Observations (from field) prior to and after to leaf-out of trees

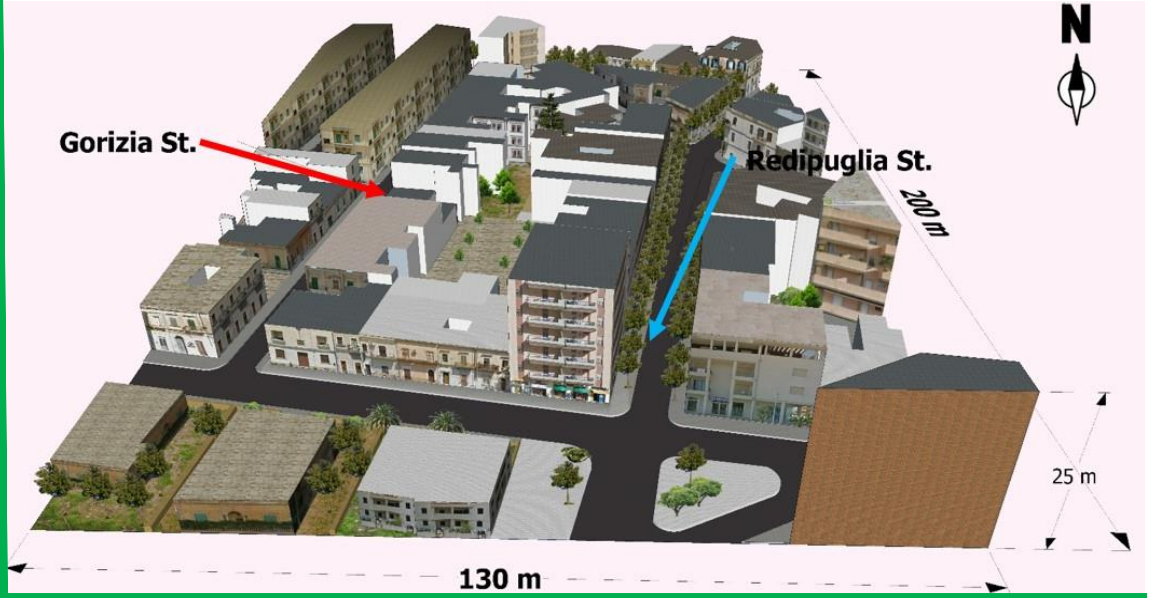
- To quantify trees effect on in-canyon
  1. **air and surface temperature**
  2. **wind**
  3. **turbulence**
  4. **air quality**

Numerical CFD simulations to assist data interpretation

- To isolate the effects of trees from meteorological conditions (particularly wind direction) observed from field measurements using different scenarios with and without trees

Study area



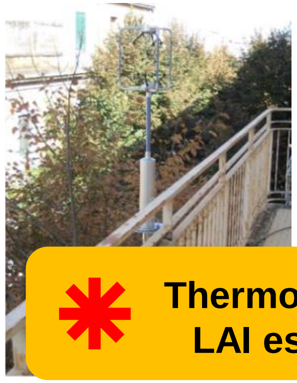


- ❑ Country: **Italy (Apulia region)**
- ❑ **City**: **Lecce** is medium size city of south Italy with about 100,000 inhabitants.
- ❑ Architectural design of Mediterranean city, consisting of **2-3 storey buildings** and **narrow** street canyons

- ❑ Study area size: 130m x 200m
- ❑ Height of buildings (H): 5 m -25 m
- ❑ Aspect Ratio (H/W): 1.10 (Gorizia St.);
  1.22 (Redipuglia St.)
- ❑ Redipuglia St. → Trees (Tilia Cordata)
- ❑ Gorizia St. → No trees

Methodology





➢ **3 Sonic anemometers GILL R3-50** (acquisition sampling frequency of 50Hz)
➢ **Thermo-hygrometer** Vaisala HMP45C (1Hz)

✱ **Thermography and LAI estimation**

11-12 October 2013 — **Campaign 1**

8-9 November 2013 — **Campaign 2**

6-7 December 2013 — **Campaign 3**

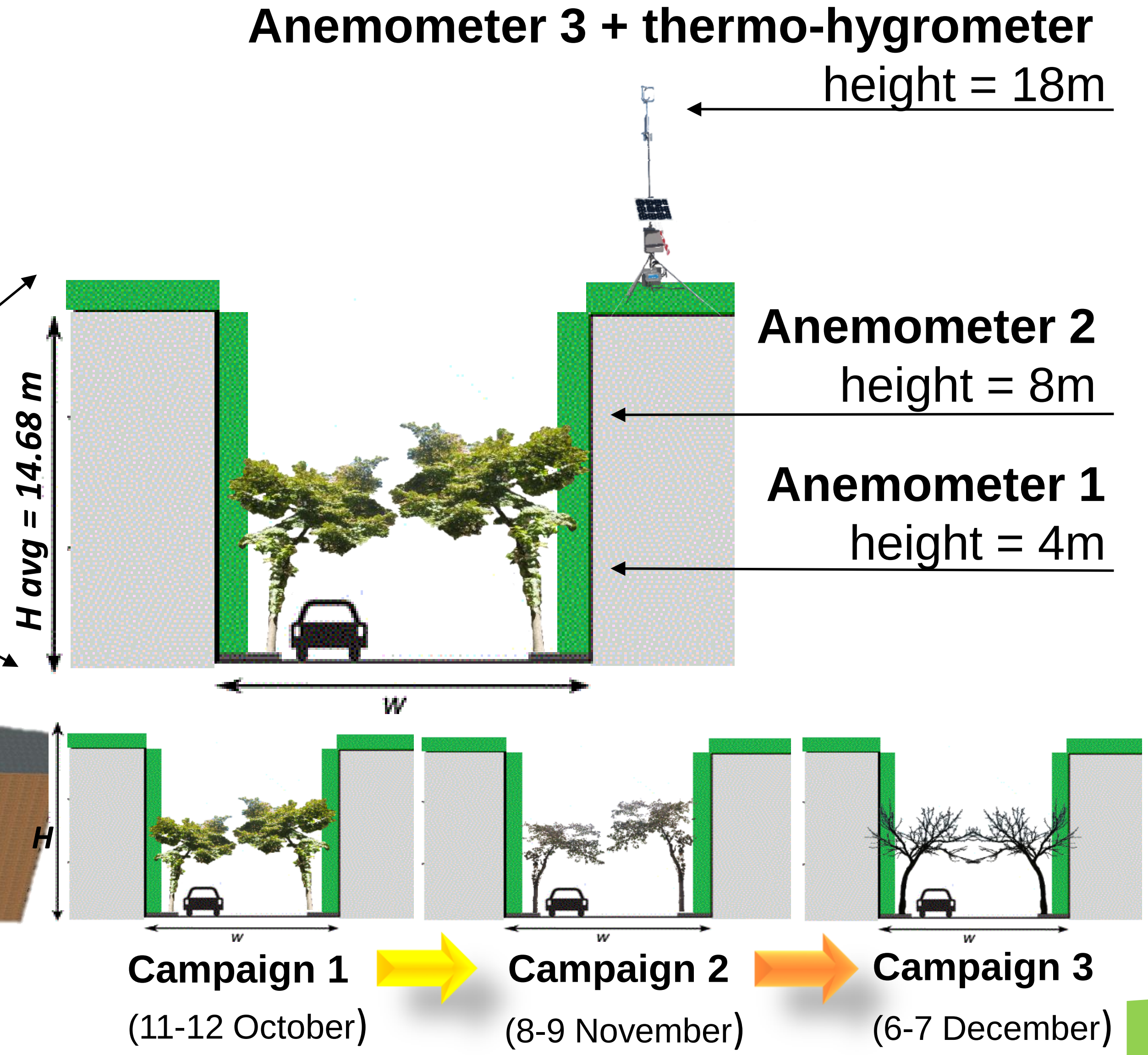

- **FLIR T620 IR thermal camera** with pinless meter for **humidity/temperature**
- **AccuPAR LP-80 ceptometer** for the **LAI estimation**

Campaign 1 **Campaign 2** **Campaign 3**



Large porosity → **Intermediate porosity** → **Low porosity**

Flow and turbulence measurements



Thermal imaging measurements

- **Thermal images were acquired every three hours during the day noon to noon**
- **12.00** (close to the **maximum surface temperature**)
- **21.00** (when the **Urban Heat Island** intensity was **maximum**)
- **before sunrise** (close to when **air temperature** was **minimum**).

Selection criteria

- **4 representative buildings** (two in Gorizia St. and two in Redipuglia St.)
- Homogeneity of construction materials (limestone)
- Absence of obstacles (balconies, eave, breastwork)
- Absence of metal or glass surfaces

Leaf area index measurements

$$LAI = \frac{\left[\left(1-\frac{1}{2K}\right)f_b - 1\right]\ln\tau}{A(1-0.47f_b)}$$

Leaf Area Index - estimated from ceptometer measurements

A: absorption coefficient of the leaves
K: extinction coefficient for the canopy (depent to χ and Θ)

Species	Leaves	Reference
Q. robur	LAI = 2.6--3.3	Kira 1975
Q. robur	3.8 $Mg_{DM}\,ha^{-1}$	Utenkova et al. 1971
Q. petraea	3.4 $Mg_{DM}\,ha^{-1}$	Oszlanyi 1983
Q. petraea	2.4–4.0 $Mg_{DM}\,ha^{-1}$	Bokhanova 1971
Q. petraea	LAI = 4.5	Rauner 1976
Q. petraea	LAI = 3.6	Ladefoged 1963
F. excelsior	LAI = 2.8	Ladefoged 1963
T. cordata	LAI = 5.3	Rauner 1976

Table 4. Leaf area (LAI) and leaf dry mass in *Quercus*, *Fraxinus* and *Tilia* forests at sites in Europe.

$$LAD = \frac{LAI}{\text{Avg. canopy height}}$$

Leaf Area Density - estimated dividing LAI by the depth of tree crown (3m in our case)

Paramether obtained from ceptometer	Description
PAR μmol m^{-2} s^{-2}	Photosynthetically active radiation
LAI m^2/m^2	Leaf area index
χ	Leaf distribution parameter refers to the distribution of leaf angles within a canopy
f_b	Fraction beam is the ratio of direct beam radiation coming from the sun radiation coming from all other source like atmosphere of reflected by the other surface
τ	It is defined as the ratio of below canopy PAR measurements to the most recent above canopy PAR value.
Θ	Zenith angle

Campaign 1

Campaign 2

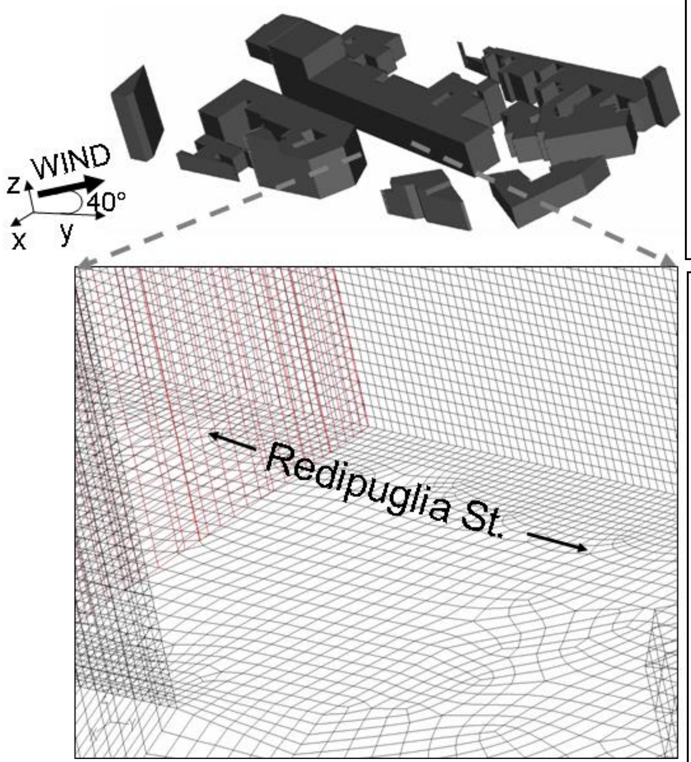
Campaign 3

Campaign 1	Campaign 2	Campaign 3
Large	Intermediate	Low
LAI = 5.21	LAI = 0.97	LAI = 0.37
LAD = 1.74	LAD = 0.32	LAD = 0.12

CFD – set-up

Meteorological conditions recorded at 21:00 (*mostly isothermal conditions*) during **Campaign 1 (11 October 2013)**

- **CFD code FLUENT**
- **3D steady-state**
- **grid**: hexahedral elements
  - ~2,000 000
  - $\delta_x=\delta_y=\delta_z=0.25$m (close to the walls)
- **RANS-Equations**
- turbulence closure scheme
  - **Reynolds Stress Model** (RSM)
- second order discretization schemes
- Line source along Redipuglia St.
  - Q = 10g/s (CO)



- **The inlet wind speed was assumed to follow a logarithmic law profile**

$$U(z)=\frac{u_*}{\kappa}\ln\left(\frac{z+z_0}{z_0}\right)$$

Wind speed U_{ref} = **2.3** ms^{-1} (approaching undisturbed, at 20m)
Wind direction = **140°**

- **Equilibrium profiles of *TKE* [m^{2}s^{-2}] and dissipation rate (*ε*) [m^{2}s^{-3}] were specified to get a fully developed flow under neutral stratification conditions**

$$TKE=\frac{u_*^2}{\sqrt{C_\mu}}\left(1-\frac{z}{\delta}\right) \qquad \varepsilon=\frac{u_*^3}{\kappa z}\left(1-\frac{z}{\delta}\right)$$

u_* = 0.17ms^{-1} is the **friction velocity**
z_0 = 0.1m is the **aerodynamic roughness length**
κ = **von Kàrmàn** constant (0.40)
δ =150m is the **computational domain height**
$C\mu$= 0.09

CFD – set-up

With trees **Without trees**

Gromke et al. 2008, Buccolieri et al. 2009, Salim et al. 2011, Buccolieri et al. 2011

- A **cell zone is defined** in which the porous media model is applied and the pressure loss in the flow is determined

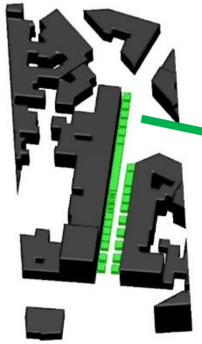
- The porous media model adds **a momentum sink in the governing momentum equations**:

$$S_i = -\left(\sum_{j=1}^{3} D_{ij}\mu v_j + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho|v|v_j\right)$$

viscous loss term + inertial loss term

S_i: source term for the i-th (x, y, or z) momentum equation
$|v|$: magnitude of the velocity
D and C: prescribed matrices

- This momentum sink contributes to the pressure gradient in the porous cell, creating a **pressure drop** that is proportional to the fluid velocity (or velocity squared) in the cell.



Permeable zone with pressure loss coefficient
λ = Cd x LAD = 0.35m^{-1}

leaf drag coefficient assumed to be 0.2

Exchange velocity calculation

$$u_e = \frac{q_v}{A_{roof}\left(\left\langle \overline{C}_{canyon}\right\rangle - \left\langle \overline{C}_{bkg}\right\rangle\right)}$$

q_V pollutant flux (kg/s) at roof level through the exchange surface A_{roof} (m^2)

$\left\langle \overline{C}_{canyon}\right\rangle$ averaged pollutant concentration within the canyon (kg/m^3)

$\left\langle \overline{C}_{bkg}\right\rangle$ background concentration (kg/m3), i.e. pollutant concentration of the incoming atmospheric flow (it can be null if this is defined zero outside the domain).

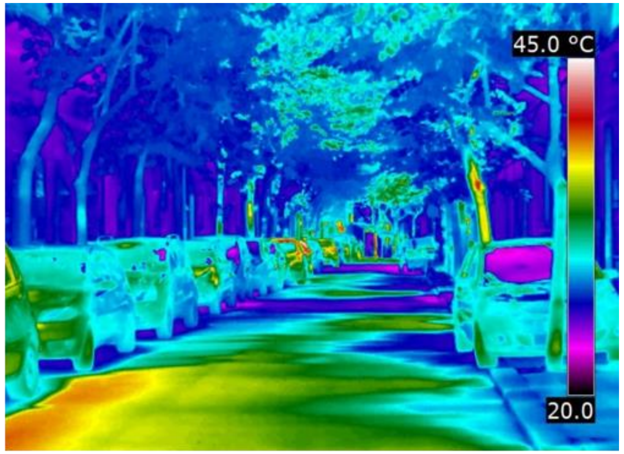
Calculation of u_e from $q_V = \int_V Q_U dV - \int_A \overline{U}_i \cdot \overline{C} n_i dA$

- V (m^3): whole volume of the canyon. Also i denotes x and y
- Q_U (kmol/m^3-s): passive scalar emission rate per unit volume within V
- A (m^2): total surface of the street sections at the border of the canopy
- $\overline{C}$ (kmol/m^3): concentration

(computed as the residual of a balance of the pollutant fluxes entering and leavening the street (i.e. in the horizontal plane) through the sides)

Experimental results: surf. temperatures

No Trees

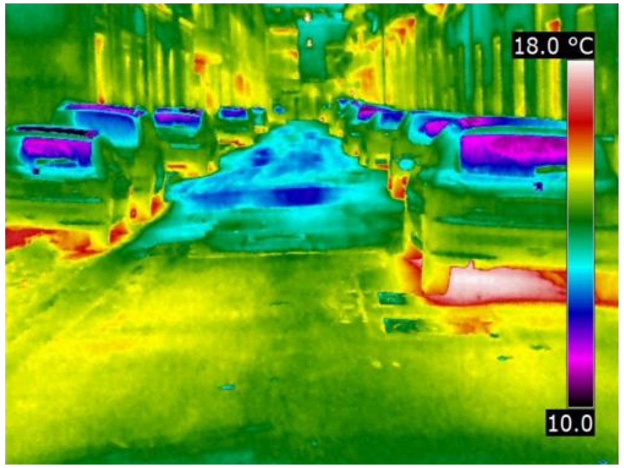


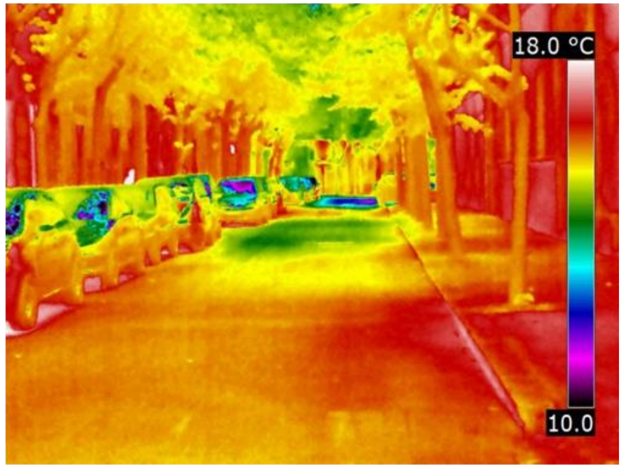
With Trees

IR images at 12am
(Campaign 1, large LAI)

Lower temperatures in Redipuglia St. during daytime

No Trees





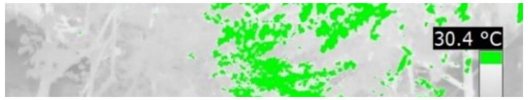
With Trees

IR images at 3am
(Campaign 3, low LAI)

Larger temperatures in Redipuglia St. during nighttime

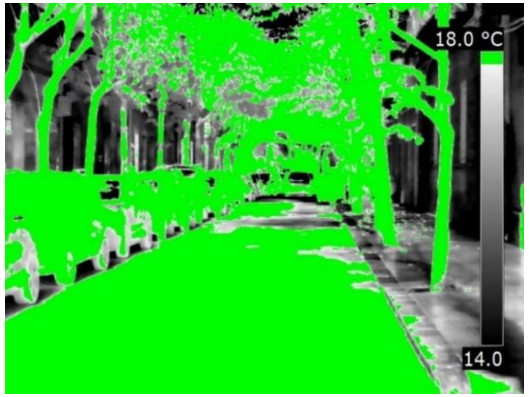
Experimental results: surf. temperatures

Campaign 1 | **Campaign 2** | **Campaign 3**



Shadowing effect

Shadowing effect



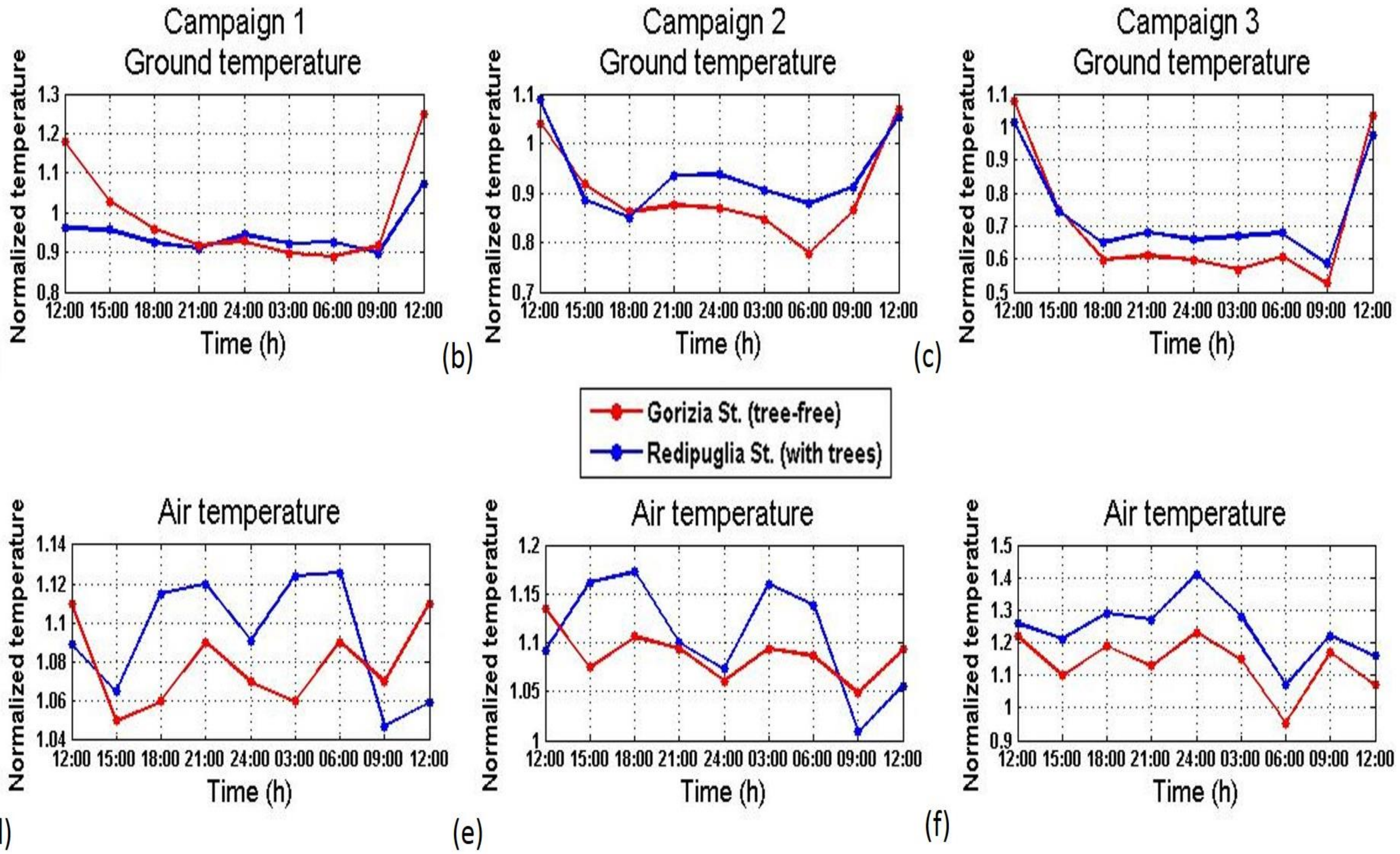
- **IR images at 12am (Campaign 1, large LAI) left (Campaign 2, intermediate LAI) middle (Campaign 3, low LAI) right**

Panoramic thermal photo at the maximum radiation during different seasons

- **IR images at 12am (Campaign 1, large LAI) left (Campaign 2, intermediate LAI) middle (Campaign 3, low LAI) right**

Green = surfaces with higher temperature than air at maximum radiation during different seasons

Air and ground temperatures



Campaign 1 (**large** LAI)

- **Trees lower air and ground temperatures during daytime**

- Slightly **larger temperatures** in Redipuglia St. **during nighttime**

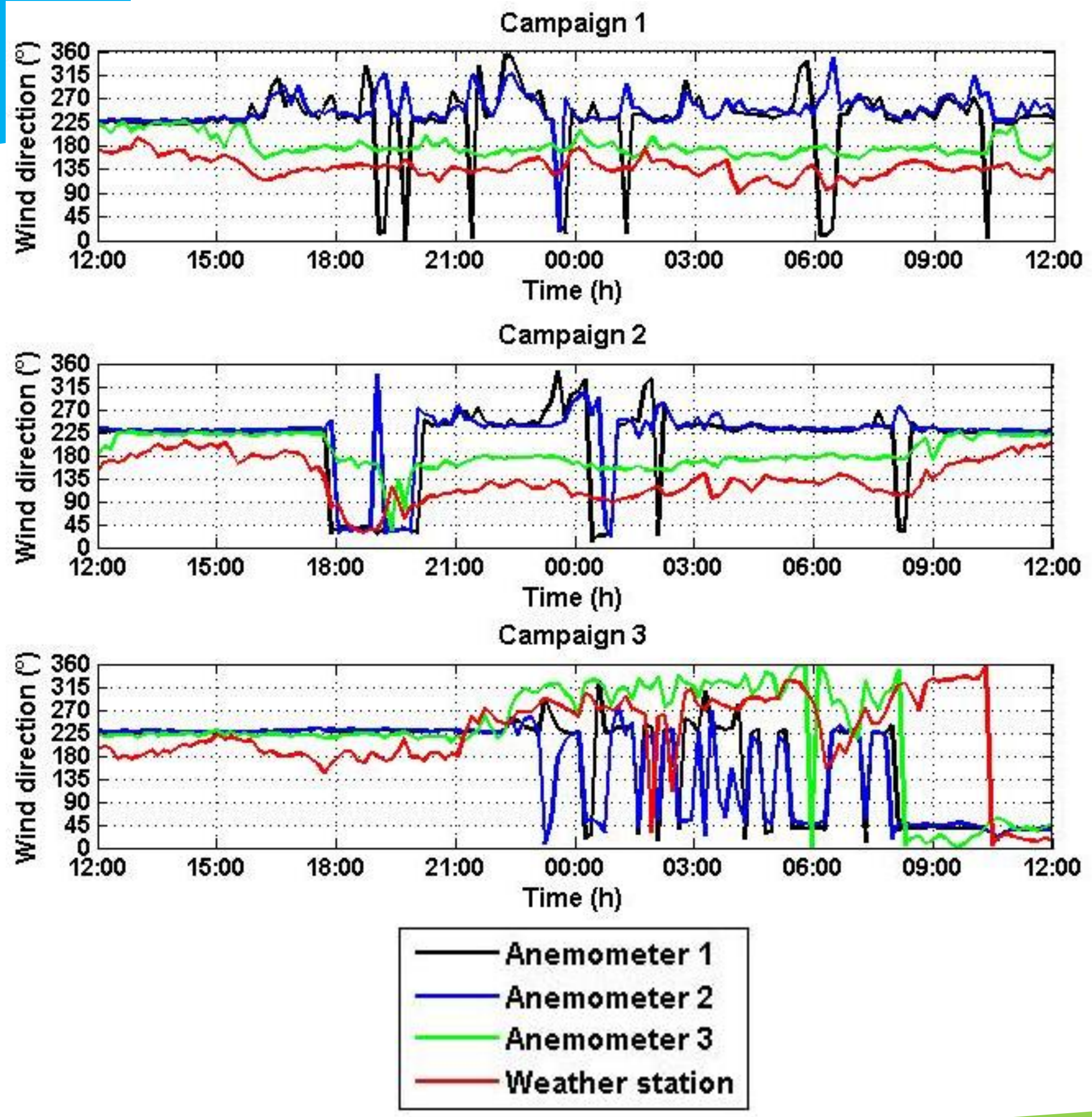
Campaign 2-3 (**intermediate** - **low** LAI)

- Cooling of trees **less pronounced during daytime**; ground temperatures were almost similar within the two streets

- **During nighttime, Redipuglia St. still experiences larger temperatures**

Wind direction

Time averaging = 10min



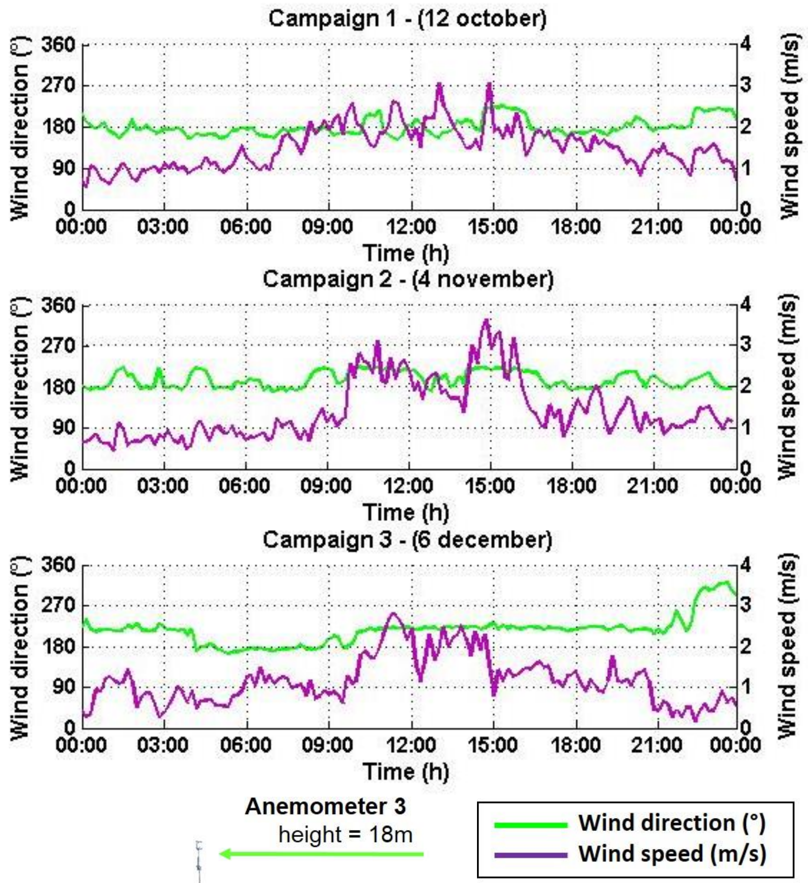
Campaign 1 (large LAI), **the interaction with trees induced wind direction fluctuations below and above tree crowns** (at Anemometer 1 and 2).

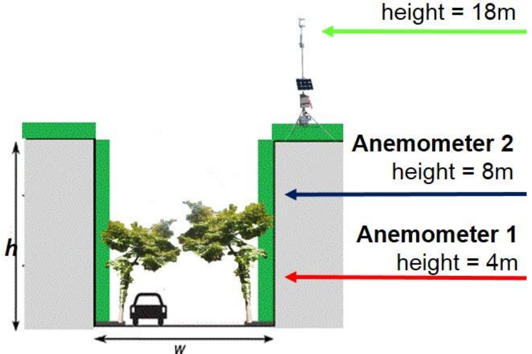
Campaign 2 (intermediate LAI): **trees structure change lowers fluctuations under the canopy**

Campaign 3 (low LAI): a **wind channelling along the street** axis (from south to north) is evident **due to the reduced influence of trees.**

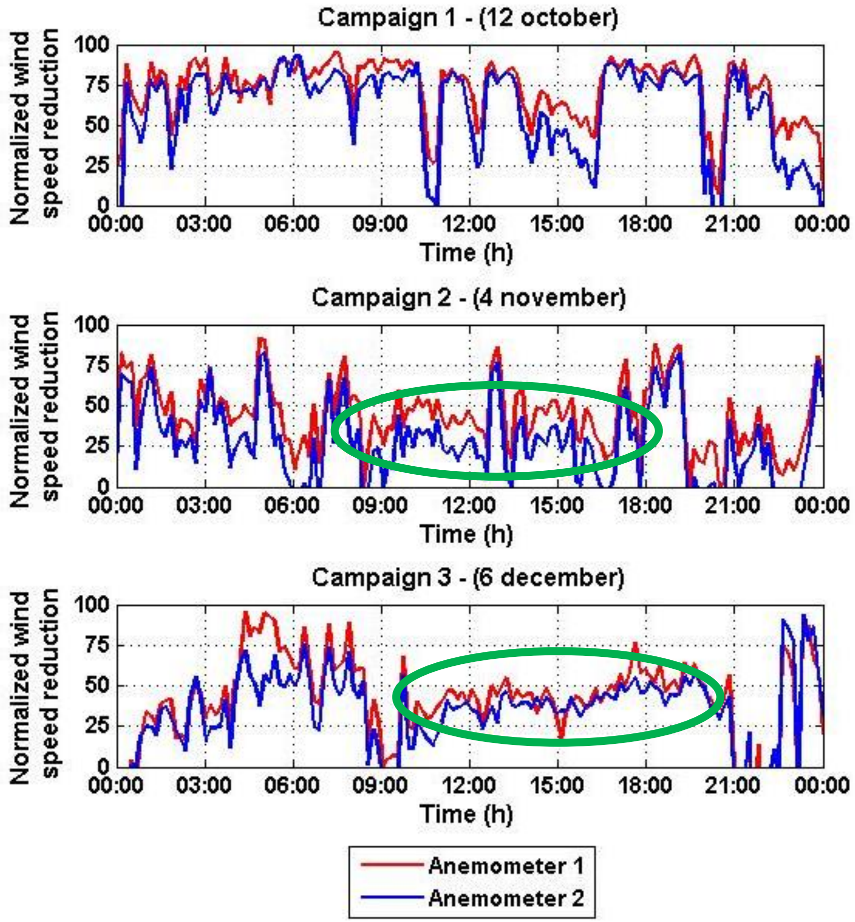
Wind speed reduction

Wind from South





Time averaging = 10min

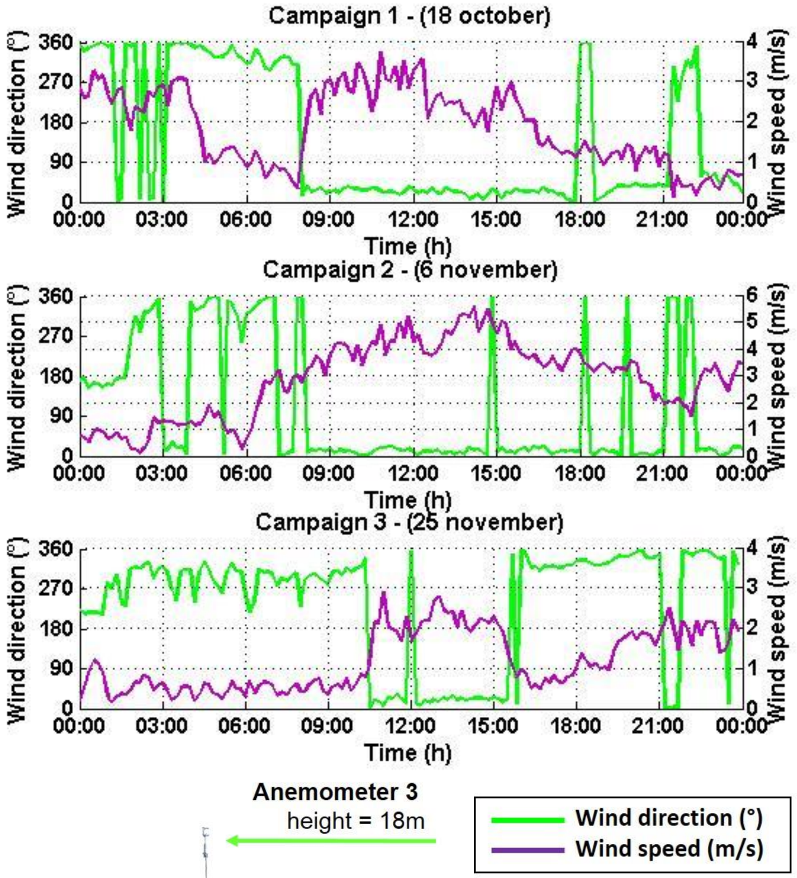


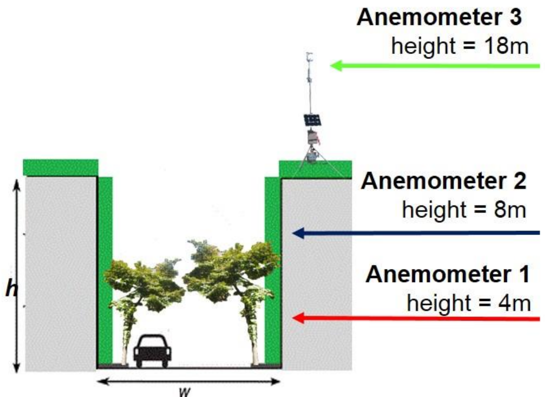
- Trees with leaves
  - A1 72%
  - A2 59%
- Trees middle leaves
  - A1 44%
  - A2 26%
- Trees without leaves
  - A1 39%
  - A2 31%

Percentage reduction of wind speed in street canyon in two different seasons in similar weather conditions

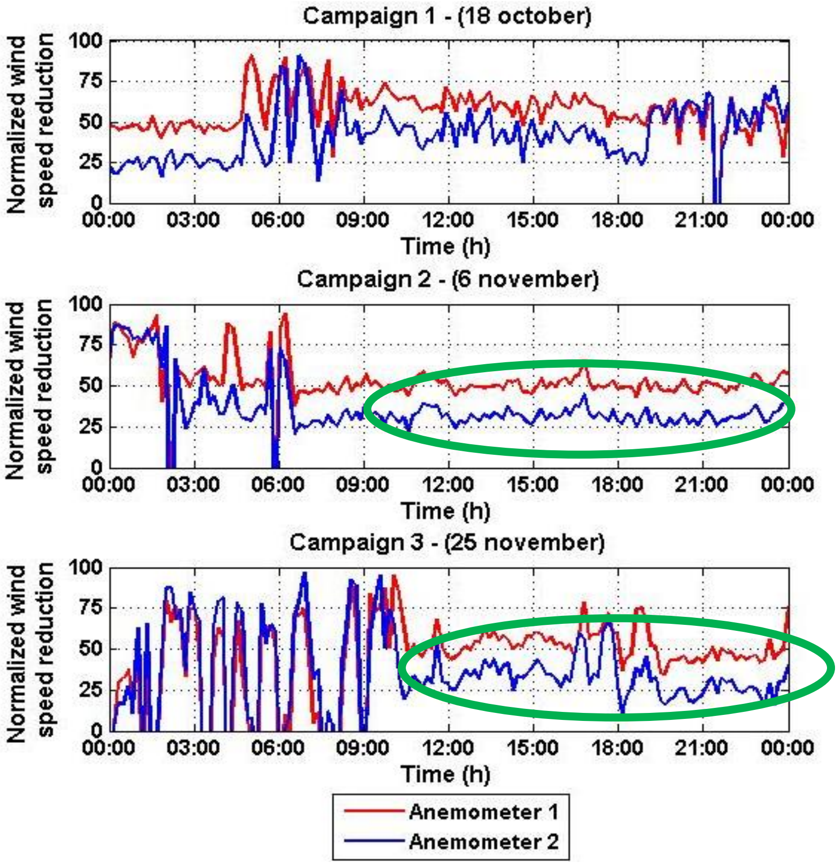
Wind speed reduction

Wind from North





Time averaging = 10min



- **Trees with leaves**
  - A1 56%
  - A2 41%
- **Trees middle leaves**
  - A1 53%
  - A2 35%

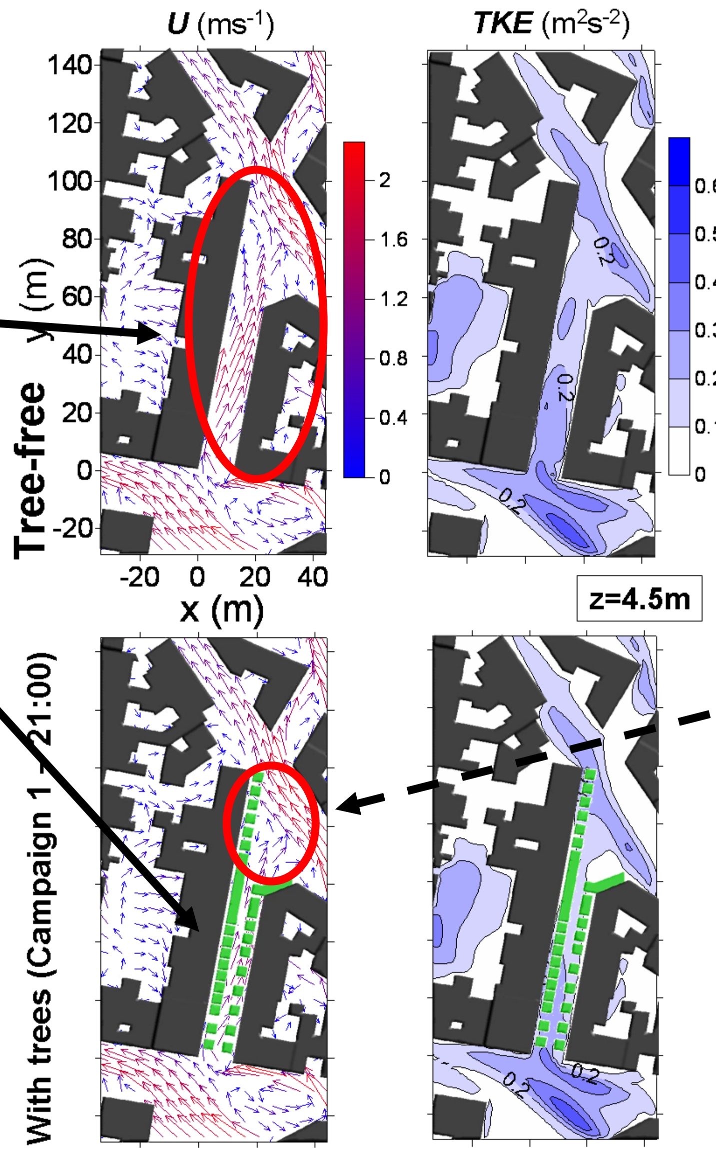
windy

- **Trees without leaves**
  - A1 40%
  - A2 32%

Percentage reduction of wind speed in street canyon in two different seasons in similar weather conditions

CFD Simulations - wind channelling

Channelling



Vectors of wind speed and contours of TKE at z=4.5m (**just below the tree crown**) obtained from CFD simulations in Redipuglia St.

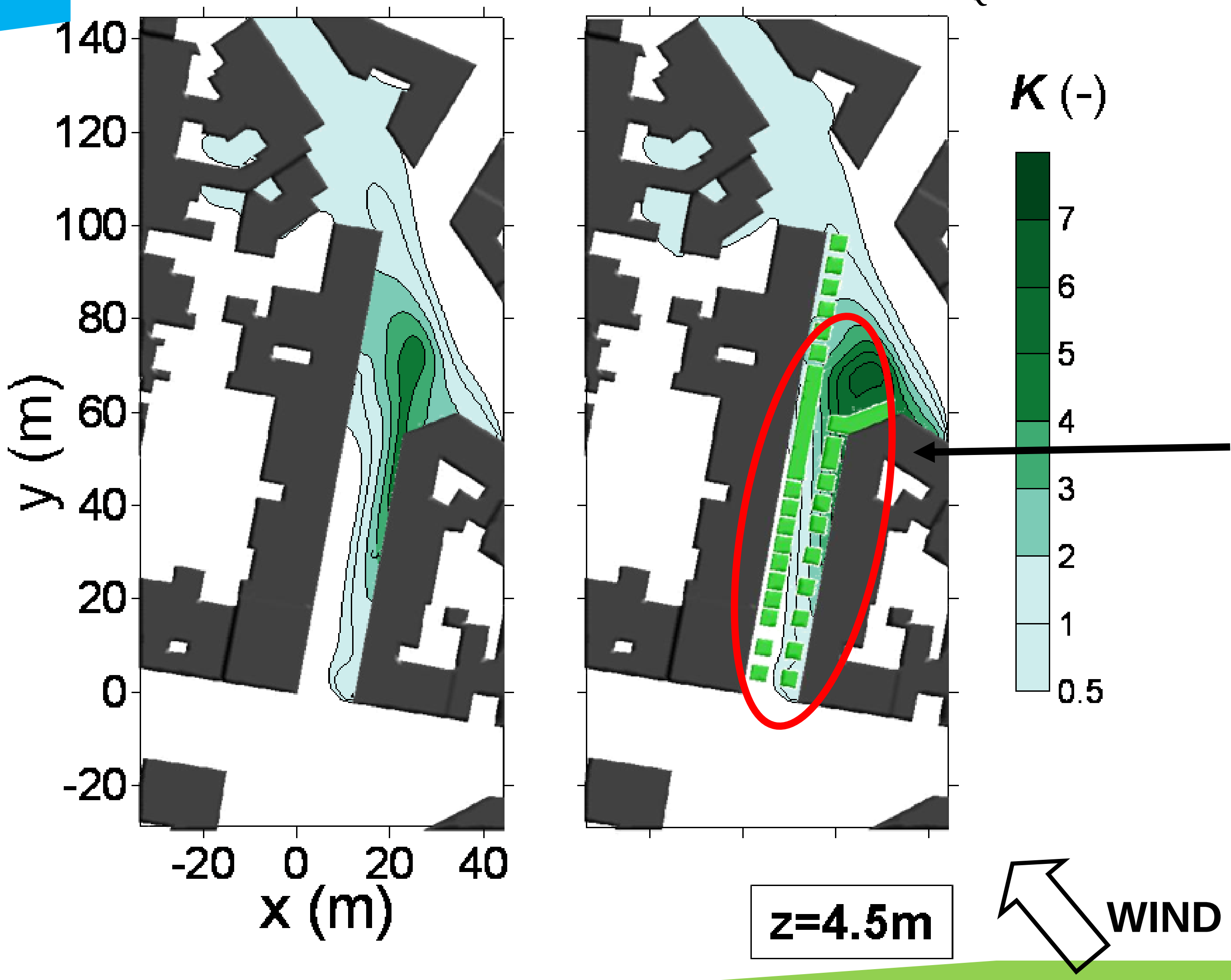
A vortex occurs leading to reverse flow at the downstream exit of Redipuglia St.

- **TKE is suppressed** especially at the upstream entry of Redipuglia St. partially explaining higher observed temperatures

WIND

CFD Simulations – concentration

$$K = \frac{C_{calc} \times H_{avg}{}^{2} \times U_{ref}}{Q}$$



Contours of normalized concentration *K* at z=4.5m (**just below the tree crown**) obtained from CFD simulations in Redipuglia St.

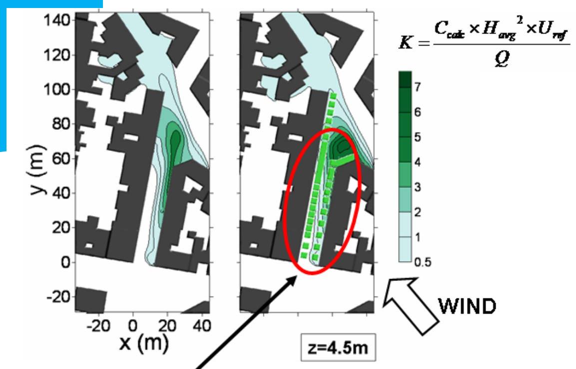
➢**Larger concentration along the street WITH TREES and at the downstream exit**

$$\frac{C_{TREE} - C_{NO\_TREE}}{C_{NO\_TREE}} \approx 20\%$$

C: averaged pollutant concentration within the canyon

CFD Simulations – concentration

$$u_e = \frac{q_v}{A_{roof}\left(\langle \overline{C}_{canyon} \rangle - \langle \overline{C}_{bkg} \rangle\right)}$$



➢Larger concentration along the street WITH TREES and at the downstream exit

$$\frac{C_{TREE} - C_{NO\_TREE}}{C_{NO\_TREE}} \approx 20\%$$

C: averaged pollutant concentration within the canyon

➢Exchange velocity variation:

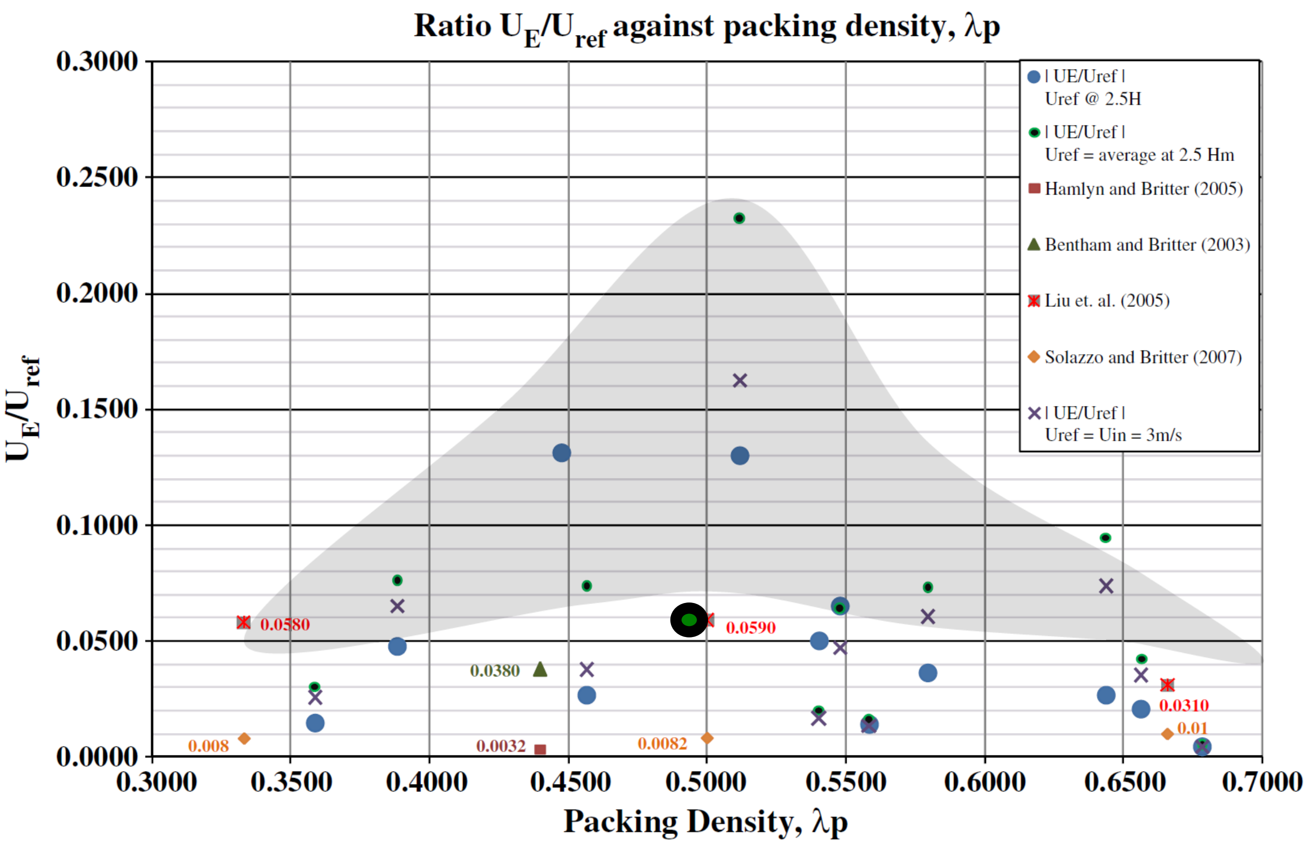
- ➢ $u_{e\_NO\ TREE}$ ~ 0.14m/s
- ➢ u_{e_TREE} ~ 0.11m/s

$$\frac{u_{e\_TREE} - u_{e\_NO\_TREE}}{u_{e\_NO\_TREE}} \approx -20\%$$

$$\lambda_p \approx 0.49$$

$$\frac{u_{e\_NO\_TREE}}{U_{ref}} \approx 0.06$$

$$\frac{u_{e\_TREE}}{U_{ref}} \approx 0.05$$



Panagiotou et al., 2013. City breathability as quantified by the exchange velocity and its spatial variation in real inhomogeneous urban geometries: An example from central London urban area. Science of the Total Environment 442, 466–477

Conclusions

- The combined use of IR **thermal images** and **air temperature probes** allowed us to investigate the **temperature distribution within street canyons with and without trees**
  - Trees are effective **in trapping heat close to the ground**. This effect during nighttime is **more important** than the **passive cooling through evapo-transpiration** leading to **increased temperatures** with respect to the tree-free case
- Using **high-frequency flow data** in combination with **CFD simulations** it has been possible to further appreciate the **effect of trees on flow, turbulence and pollutant dispersion within the street canyon**
  - A significant **windbreak effect** is observed in the street canyon with trees (confirmed by simulations)
  - The **wind channeling** typical of the specific approaching wind directions is **still maintained in the presence of trees**, but with **reduced wind speed** and **enhanced concentrations** with **reverse flow** within the street

Ongoing work

Infrared photo

Digital photo

- ❑ Thermal images were acquired every three hours during 48 hour
- ❑ More than 1300 photos taken ground and buildings façade temperature

- ❑ Accurate temperature measurements

- ✓ **Determining reflected apparent temperature –** reflector method
- ✓ **Determining the emissivity of materials**

- ❑ Study area in Helsinki – Finland Kumpula Kampus, Ernst Lindelofin katu

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Ongoing work

Infrared photo

Digital photo

- ❑ Thermal images were acquired every three hours during 48 hour
- ❑ More than 1300 photos taken ground and buildings façade temperature

- ❑ Flow and turbulence

2 sonics levels within street canyon inside trees line

Just above trees crown - 5m
Inside canopy - 3m

SMEAR III - 31 m tower 4 km from down town Helsinki instrumented at several heights yielding profiles of temperature wind radiation components

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Helsinki (Finland) July 7-12 2014

Aknowledgements

The authors wish to thank the Dipartimento di Ingegneria dell’Innovazione - University of Salento for making available ANSYS Fluent

- **Computational time**: about **one day** for a single simulation case with 8 CPU

- **CFD simulations with buoyancy**:
  - **refine the mesh close to the heated walls** to capture the heat fluxes (the gradient of temperature is very high). In our case we used 0.25m (about 0.015H with H the average height of the buildings of the street canyon)
  - **a better convergence** is achieved starting the simulation from the non-buoyancy solution and after that including the temperature equation without buoyancy (thermal expansion coefficient β=0). And finally taking into account the buoyancy ($\beta = 0.0033\ K^{-1}$ in our case)
  - **temperature differences were not large** (the maximum temperature difference between air and wall was less than 2°C), so the effect of buoyancy was low. It is expected that **larger differences (larger Ri) may enhance the effect of buoyancy on flow and turbulence**

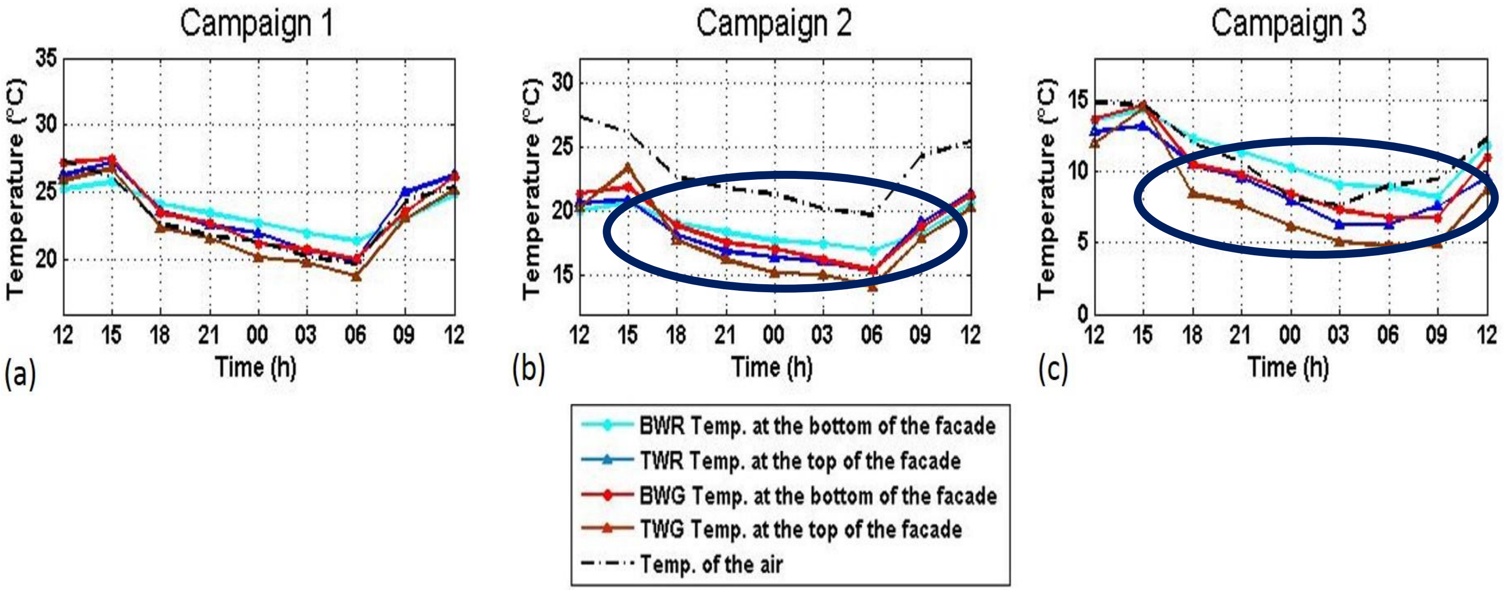
- Nevertheless the used **methodology which combines the effects of trees and the effect of buoyancy** was successful in predicting a decrease of TKE in the presence of trees as observed from field measurements

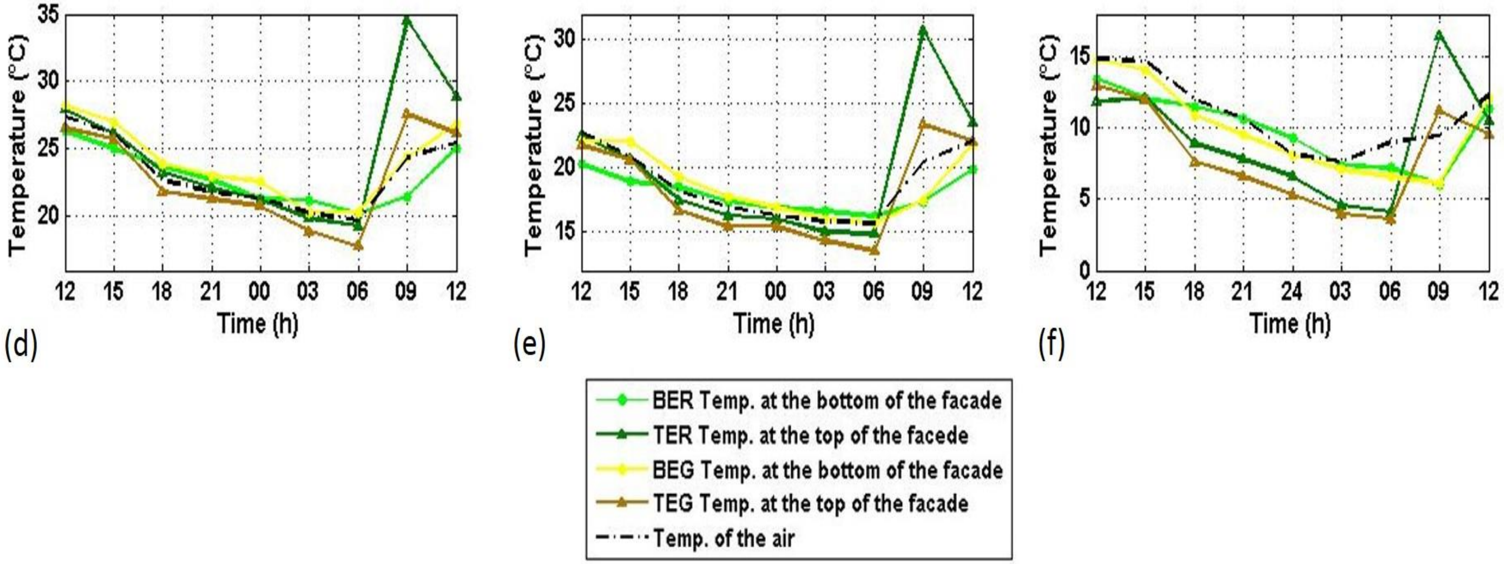
- **This encourages the use of CFD technique to isolate the effects of trees, buoyancy etc.** from meteorological conditions and other variables which is unfeasible from field measurements

Temperature of building façades

Exposed to East

Exposed to West





Campaign 1

Redipuglia St. bottom is warmer than top only at noctural hours (top experienced larger temperatures than bottom due to trees shadow during daytime)

Gorizia St.bottom is warmer than top (except at 10:00am)

Campaign 2-3

NO inversion was found in Redipuglia St. as observed during Campaign 1

The **old buildings** stored a lot of **intertiazial moinsture** because of the **thermal bridge – especially during campaign 2 (previous days to the campaign 2 were rainy)**