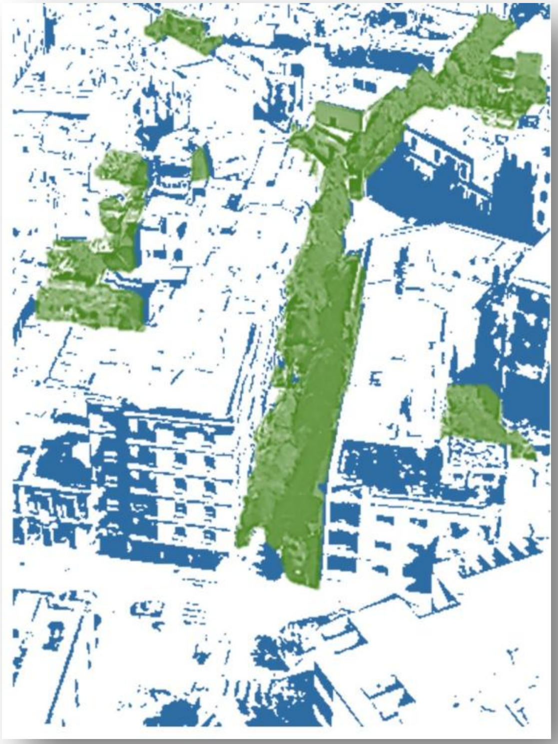
iCUC 9th International Conference on Urban Climate

20th-24th July 2015
Toulouse France

On the exchange velocity in street canyons with tree planting



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Ventilation indicators

20th-24th July 2015 Toulouse France

Overview of CFD studies on urban wind flow and outdoor ventilation of simplified urban configurations, including study of integral parameters for ventilation performance

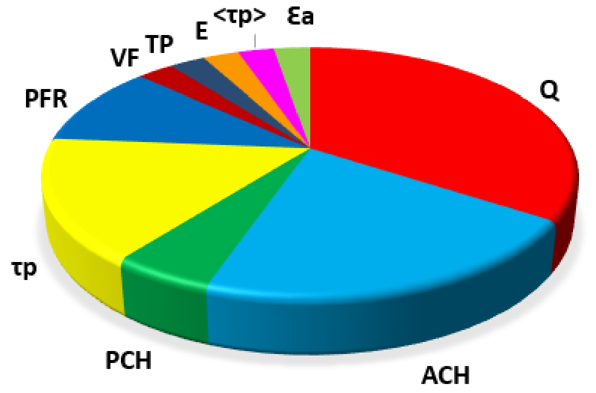
(Mod. Ramponi et al., 2015)

Authors (year)	Configuration	Evaluation parameter	Validation	Sensitivity analysis
Skote et al. (2005)	3D/Circular block with 2 or 4 sectors	Q	Y (WT)	Gridres, Wdir, Street.num.
Liu et al. (2005)	3D/Street canyon	τ_p, ACH, PCH	Y (WT)	Canyon AR
Li et al. (2005)	2D/Street canyon	ACH	Y (WT)	Canyon AR
Blocken et al. (2007)	3D/2 parallel buildings	Q	Y (WT)	Gridres, Buildgeom, Street width
Bady et al. (2008)	3D/2 buildings, aligned and staggered array	PFR, VF, TP	N	Buildgeom, Street width, Wdir, Dom.height
Blocken et al. (2008)	3D/2 buildings in V-arrangement	Q	Y (WT)	Gridres, Wdir, Street width
Cheng et al. (2008)	2D/Street canyon	τ_p, ACH, PCH	Y (WT)	Gridres, Canyon AR, Discr.ord.
Bu et al. (2009)	3D/Street canyon	ACH	N	Wdir, Canyon AR
Hang et al. (2009a)	3D/Circular, square, rect. city model	Q	Y (WT)	Gridres, Citygeom, Street.num, Wdir
Hang et al. (2009b)	3D/Circular, square, rect. city model	Q, ε_a, τ_p	Y (WT)[b]	Citygeom, Street.num, Wdir
Hang et al. (2010a)	3D/Long street models	Q, E	Y (WT)	Street width, Street length
Hang et al. (2010b)	3D/Long street models	Q, ACH	Y (WT)	Buildheight, Street width
Hang & Li (2010a)	3D/Aligned array	Q, ACH	Y (WT)	Gridres, Buildgeom, λ_p, Wdir
Hang & Li (2010b)	3D/Aligned arrays of cubes	Q, ACH	Y (WT)	Num of rows, Gridres
Buccolieri et al. (2010)	3D/Aligned array of cubes	Q, τ_p	Y (WT)	Gridres, λ_p
Moonen et al. (2011)	3D/Courtyard	Q	N	Court.length, Wdir.
Hang et al. (2012a)	3D/Aligned array	PFR	Y (WT)	Buildheight, Num.rows.array
Hang et al. (2012b)	3D/Long street models	τ_p, $<\tau_p>$	Y (WT)	Gridres, Buildheight, Street length
Hang et al. (2013)	3D/aligned arrays	Q, τ_p, PFR	Y (WT)	Street roof geom.
Lin et al. (2014)	3D/Aligned & staggered arrays	Q, ACH, PFR	Y (WT)	Turb.mod, Buildheight, Array size, Wdir.

LES = Large eddy simulation; Dyn. = dynamic Smagorinsky-Lilly SGS model; Y = yes; N = no; Pass. = passive; Hom.em. = homogeneous emission method; Q = flow rate; τ_p = effective local mean age of air; ACH = air change rate; PRF = purging flow rate; VF = visitation frequency; TP = residence time; PCH = pollutant exchange rate; ε_a = air exchange efficiency; E = total energy density; $<\tau_p>$ = spatially averaged mean age of air; WT = wind tunnel; Gridres. = grid resolution; Wdir. = wind direction; Street.num. = number of streets; Canyon AR = canyon aspect ratio; Buildgeom. = building geometry; Dom.height = domain height; Discr.ord. = order of discretization scheme; Citygeom. = city geometry; Buildheight = building height; λ_p = packing area density; Num. of rows = number of rows; Court.length = courtyard length; Num.rows.array. = number of rows in array; Street roof geom. = street roof geometry; Turb.mod. = Turbulence model.

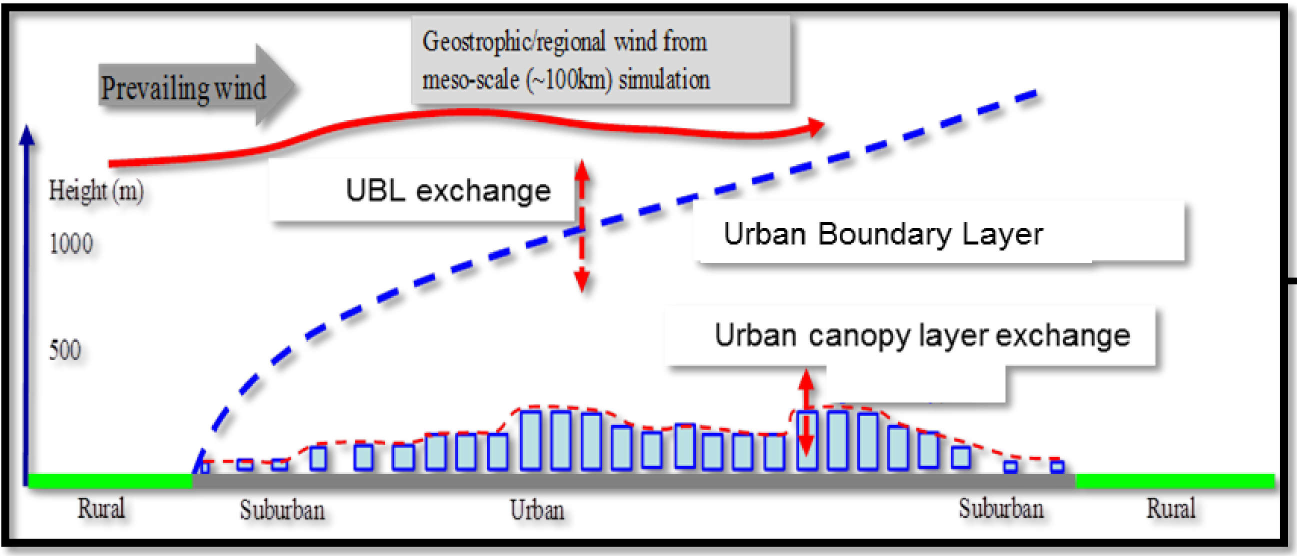
❖ Evaluation parameters

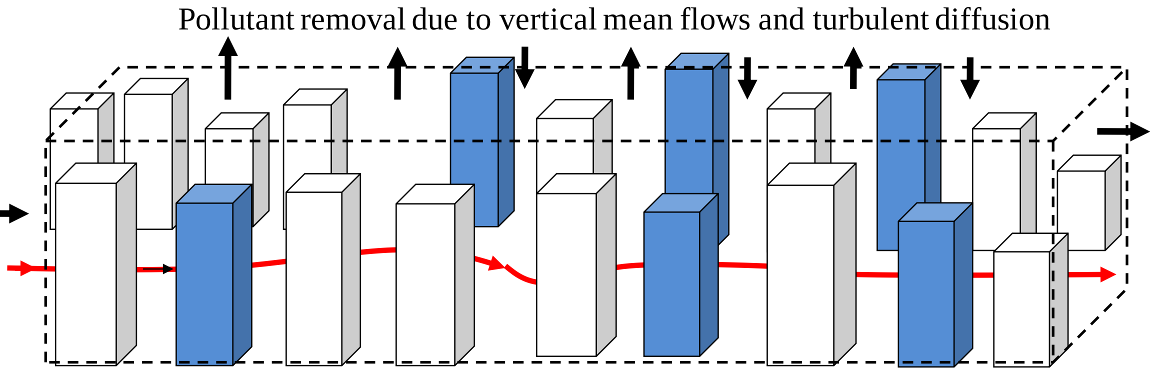
- ✓ **More than 10 different parameters were used in the literature**
- ✓ **Most studies performed are based on steady RANS equations and on successful validation of these simulations with wind tunnel measurements**
- ✓ **Most of them considered idealized/regular geometries**



City breathability

The recent developed concept of **CITY BREATHABILITY** has the appeal to be useful for flow modellers, urban planners and architects during the design of new urban areas since it captures the effect of building configuration and shape on flow and turbulence.





Exchange velocity

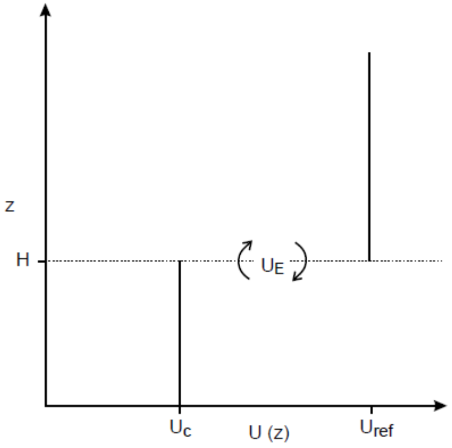
(Benthan and Britter, 2003)

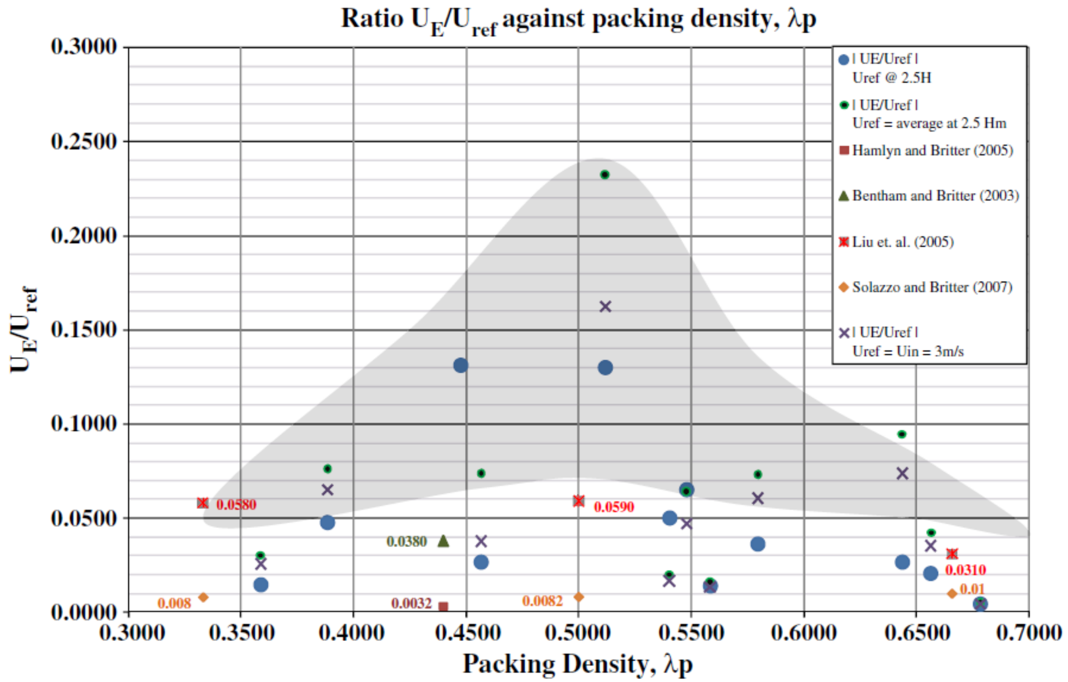
Exchange velocity defined either by the **average velocity of mass transfer into or out of the urban canopy at a plane of interface between the in-canopy and above-canopy flows**, or by the **momentum flux transfer process within a control volume.**

(Hamlyn and Britter, 2005)

Applied the model concept of exchange velocity as a **ratio of the momentum flux to the difference between the mass flux above and below the canopy top**

$$U_e = \frac{\iint \left(\rho \overline{u'w'} + \rho u w\right) dS}{\rho A_c \left(U_{ref} - U_c\right)}$$





Plot of the exchange velocity coefficients U_E/U_{ref} against the packing density λ_p in different studies and for different definitions of U_{ref}.

Panagiotou et al., 2013)

Exchange velocity

(Salizzoni et al., 2009)

(Buccolieri R. Salizzoni P., Soulhac L., Garbero V., Di Sabatino S., 2015: The breathability of compact cities. *Urban Climate*, **13**, 73–93)

u_e is regarded as an **exchange ratio that can be used as a surrogate for the complex mass transfer processes between the canopy and the overlying atmosphere**

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

$$q_V = \iint_{A_{roof}} \left(\overline{c}.\overline{w} + \overline{c'w'}\right) dA$$

pollutant flux at roof level through the exchange surface A_{roof}

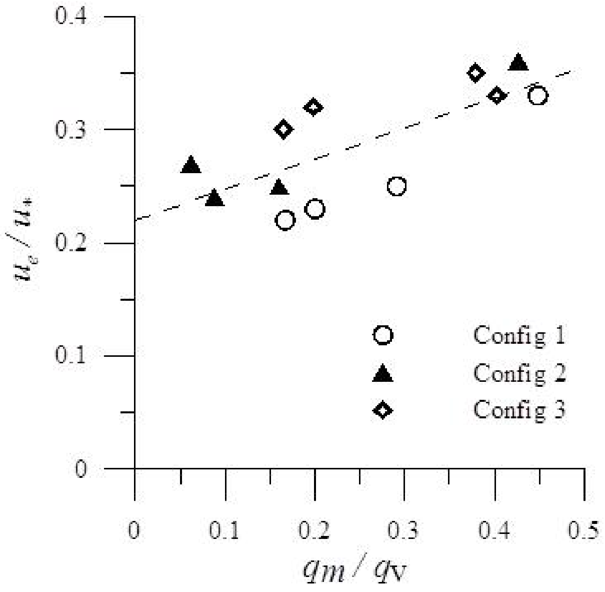
$$q_m = \iint_{A_{roof}} \overline{c}.\overline{w} dA$$

MEAN pollutant flux

$$q_T = \iint_{A_{roof}} \overline{c'w'} dA$$

TURBULENT pollutant flux

- u_e calculated for compact cities (λ_p=0.59-0.69) for various wind directions θ
- ***u_e* is about 2-5% of *U_{ref}***, a range that compares favourably well to those reported by Solazzo and Britter (2007), Hamlyn and Britter (2005) and Panagiotou et al. (2013)



$$\frac{u_e}{u_*} = 0.27\frac{q_m}{q_V} + 0.22$$

indicates that the increase of $\frac{u_e}{u_*}$ is related to an increased contribution of the **mean fluxes**, that generally increase with θ

represents the **turbulent counterpart** of the exchange which holds when the mean vertical flow is suppressed

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

Redipuglia St. (study site)

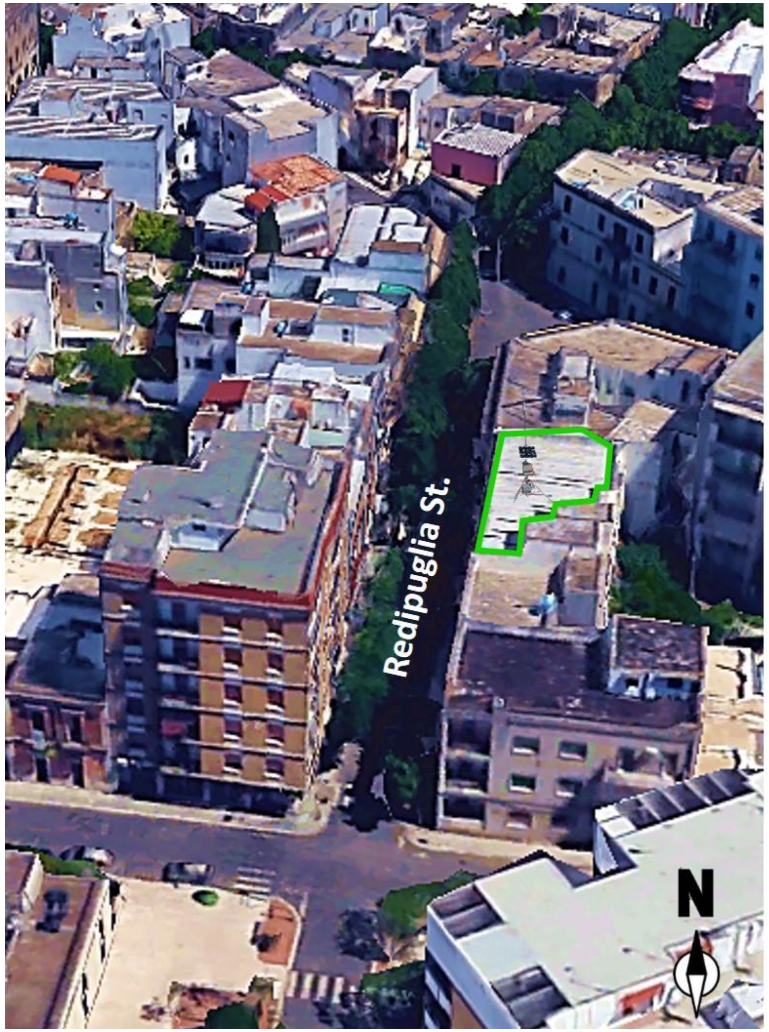
Lenght: 100m

Width (W): 12m

Heights of buildings (H): 5-25m

H/W: **1.22**

Trees (Tilia Cordata)



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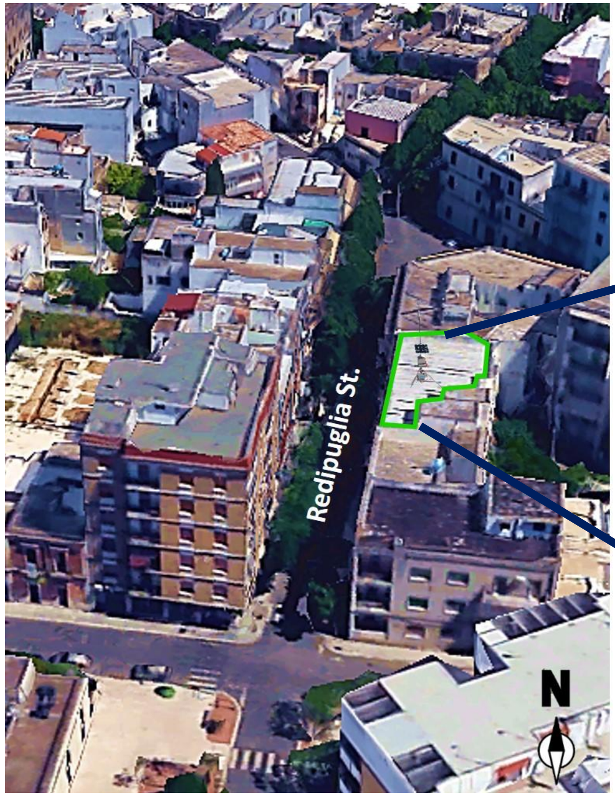
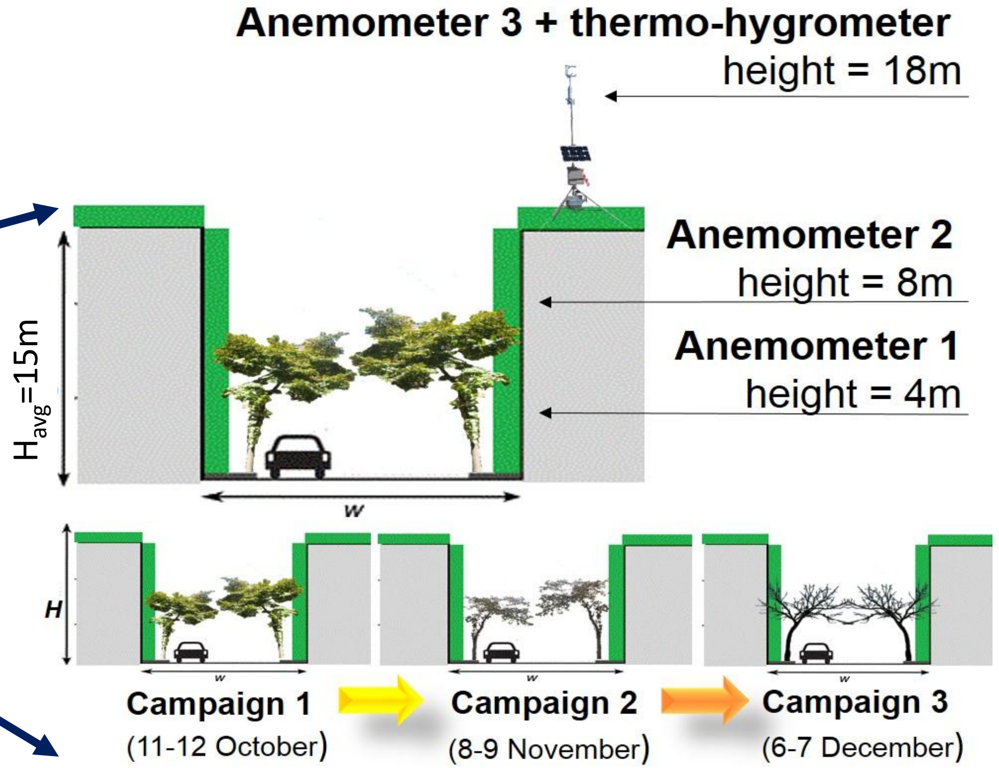
Field measurements

Field campaign: 11 October – 6 December 2013





	Campaign 1 (Large)	Campaign 2 (Intermediate)	Campaign 3 (Low)
LAI (m^2m^{-2})	5.21	0.97	0.37
LAD (m^2m^{-3})	1.74	0.32	0.12

Pappaccogli G., Buccolieri R., Maggiotto G., Leo L.S., Rispoli G., Micocci F., Di Sabatino S. 2014. The effects of trees on micrometeorology in a medium-size Mediterranean city: in situ experiments and numerical simulations. Proc. ASME 2014 4th Joint US-European Fluids Engineering Division Summer Meeting and 11th International Conference on Nanochannels, Microchannels, and Minichannels, Chicago (Illinois, USA), 3-7 August.

Exchange velocity from measurements

$$U_e = \frac{\iint (\overline{\rho u'w'} + \rho uw) dS}{\rho A_c (U_{ref} - U_c)}$$

$\overline{\rho u'w'}$: Reynolds shear stresses
U_{ref}: reference velocity
U_c: in-canopy velocity
A_C: exchange area

(Hamlyn and Britter, 2005)

Our work

$$U_e / U_{ref} = \left| \frac{\overline{u'w'} + uw}{U_{ref}(U_{ref} - U_c)} \right|$$

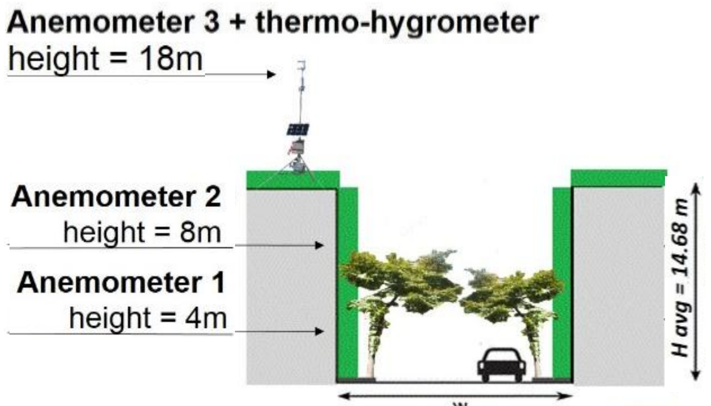
$\overline{u'w'}$: Reynolds shear stresses at Anemometer 2
(the available position closest to the exchange interface)
U_{ref}: reference velocity at 2.5H
U_c: in-canopy velocity

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{(z-d)}{z_o}$$

$H \sim 15$m: average building height
u_*: friction velocity @ Anemometer 3
d=H/3: displacement height
z_0: 0.6m

$$U_C = \frac{U_1 + U_2}{2}$$

U_1: average velocity at Anemometer 1
U_2: average velocity at Anemometer 2



Exchange velocity from CFD simulations

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

- **Reynolds Stress Model** (RSM)

second order discretization schemes

line source: emission rate Qu

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

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

$$\varepsilon=\frac{u_*^{\,3}}{\kappa z}\left(1-\frac{z}{\delta}\right)$$

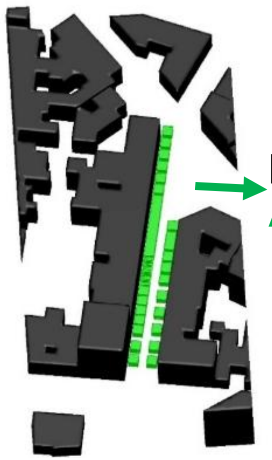
u_* : **friction velocity**

z_0 = 0.1m is the **aerodynamic roughness length**

κ = ***Von Kàrmàn*** constant (0.40)

δ =150m is the **computational domain height**

Cμ= 0.09



Permeable zone with pressure loss coefficient

λ_{fs}= Cd x LAD$_{meas.}$ = 0.35 (large LAI) – 0.024 m^2m^{-3} (low LAI)

leaf drag coefficient assumed to be 0.2

$$\frac{\lambda_{fs}}{\lambda_{wt}} = Model\ scale$$

E.g. for M = 1:150 (model scale of CODASC experiments and our previous simulations), λ_{wt} = 52.5m^{-1}

Gromke, 2011 (Environmental Pollution 159, 2094–2099)

Exchange velocity calculation

$$\frac{u_e}{U_{ref}(2.5H)}=\frac{q_v}{U_{ref}A_c\left(\langle\overline{C}_{canyon}\rangle-\langle\overline{C}_{bkg}\rangle\right)}$$

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

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

$\langle\overline{C}_{bkg}\rangle$ 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. *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 lateral sides

Results: windbreak effect

$$\left(1 - \frac{U_1}{U_3}\right) \times 100 = nrU_1$$

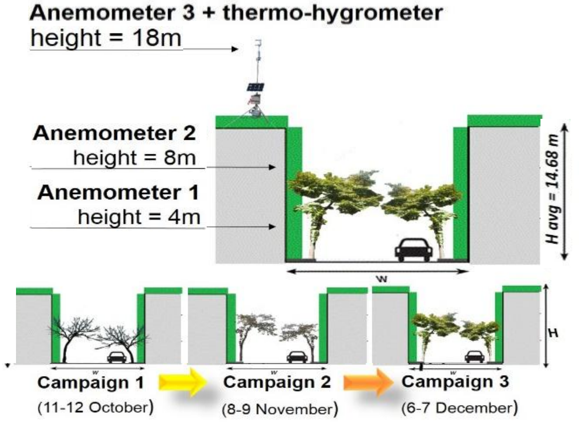
North-South wind

U_1 is the longitudinal wind speed recorded at Anemometer 1

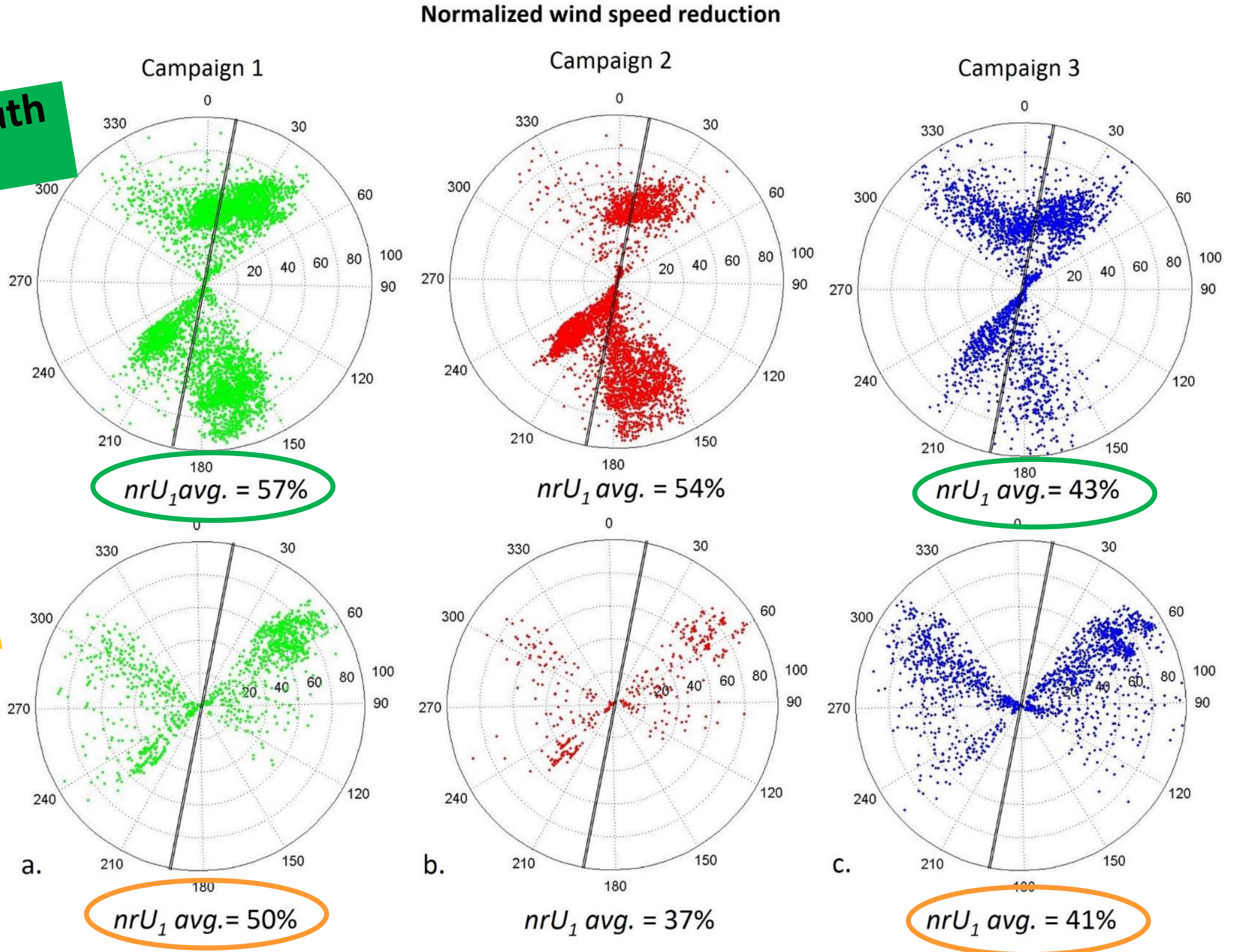
U_3 is *wind* directions refer to those recorded at Anemometer 3 (roof level)

nrU1 is the normalized percentage reduction of wind speed

West-East wind



- Campaign 1 – large LAI
- Campaign 2 – Intermediate LAI
- Campaign 3 – low LAI



Results: Exchange velocity

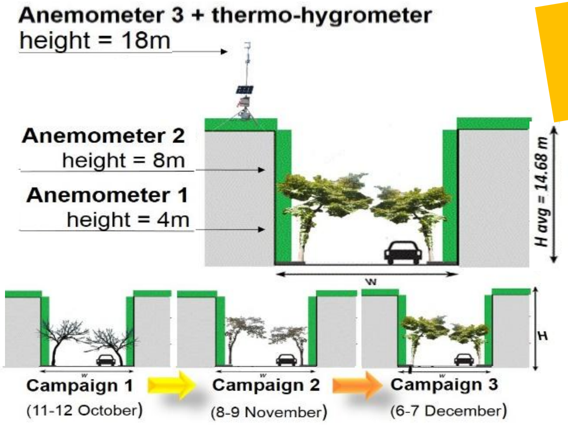
$$U_e/U_{ref} = \left| \frac{\overline{u'w'} + uw}{U_{ref}(U_{ref} - U_c)} \right|$$

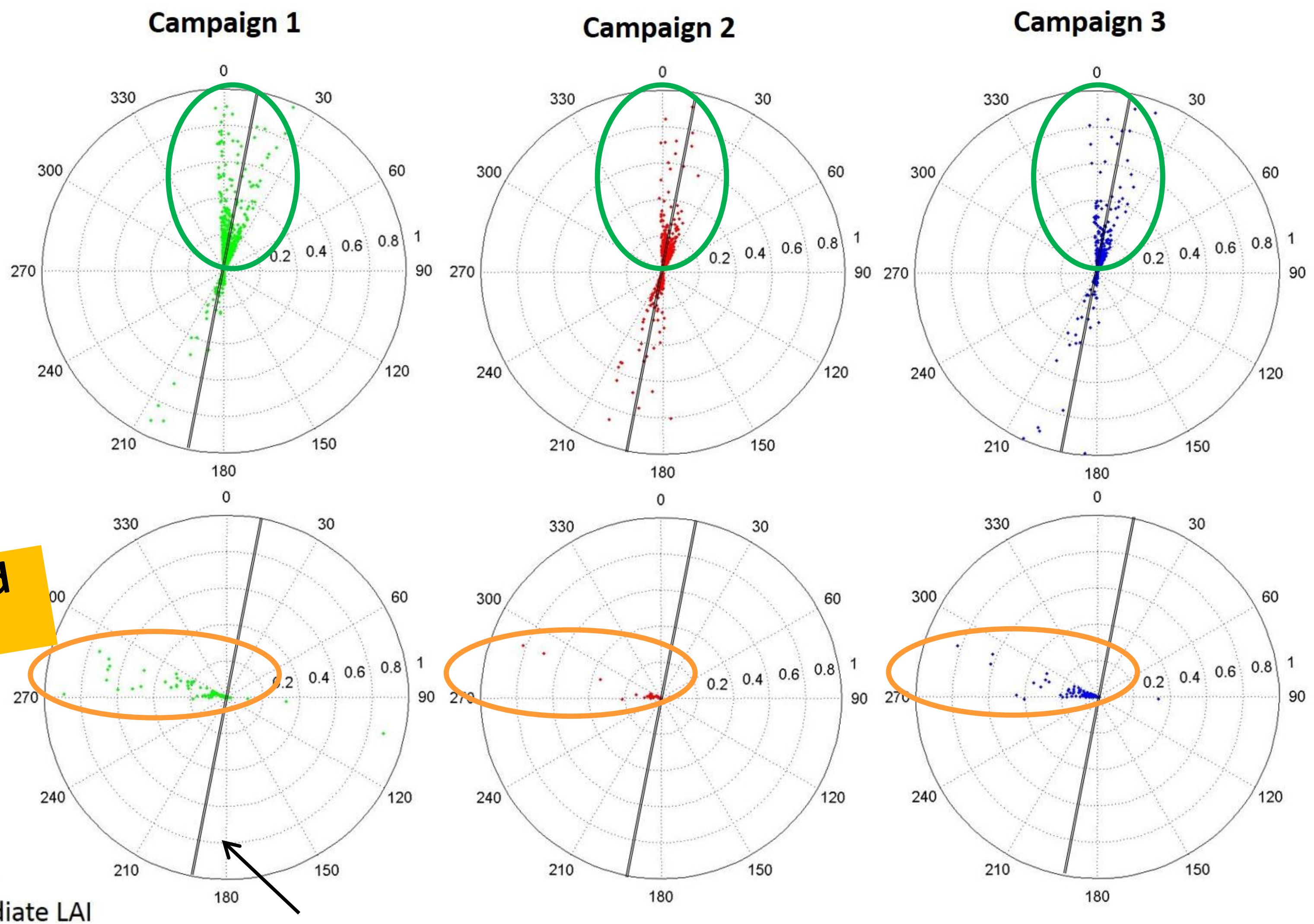
We focus on

Parallel wind
WD: 11° ± 15°

Perpendicular wind
WD: 281° ± 15°

Wind directions from Anemometer 3





- Campaign 1 – large LAI
- Campaign 2 – Intermediate LAI
- Campaign 3 – low LAI

(**11°**: ***street axis orientation with respect to the North***)

Results: Exchange velocity

$$U_e/U_{ref} = \left| \frac{\overline{u'w'} + uw}{U_{ref}(U_{ref} - U_c)} \right|$$

NIGHT	Parallel			Perpendicular			
	Mean	Std	*N_val*	Mean	Std	*N_val*	
Campaign 1	0.18	0.19	172	0.16	0.20	34	
Campaign 2	0.13	0.15	104	0.34	0.39	5	**all**
Campaign 3	0.14	0.17	34	0.05	0.06	41	
Campaign 1	0.21	0.22	99	0.16	0.20	34	
Campaign 2	0.17	0.18	48	0.34	0.39	5	**<2**
Campaign 3	0.14	0.18	31	0.07	0.07	25	
Campaign 1	0.16	0.14	43	NaN	NaN	0	
Campaign 2	0.12	0.12	30	NaN	NaN	0	**2<U_{ref}<4**
Campaign 3	0.09	0.01	3	0.03	0.02	14	
Campaign 1	0.10	0.04	30	NaN	NaN	0	
Campaign 2	0.06	0.02	26	NaN	NaN	0	**>4**
Campaign 3	NaN	NaN	0	0.01	0.01	2	

DAY	Parallel			Perpendicular			
	Mean	Std	*N_val*	Mean	Std	*N_val*	
Campaign 1	0.15	0.15	166	0.23	0.24	6	
Campaign 2	0.13	0.09	99	0.07	0.00	1	**all**
Campaign 3	0.13	0.12	137	0.05	0.09	12	
Campaign 1	0.32	0.24	31	0.28	0.24	5	
Campaign 2	0.25	0.17	7	0.07	0.00	1	**<2**
Campaign 3	0.25	0.20	24	0.17	0.21	2	
Campaign 1	0.10	0.07	82	0.00	0.00	1	
Campaign 2	0.13	0.09	46	NaN	NaN	0	**2<U_{ref}<4**
Campaign 3	0.12	0.09	85	0.03	0.02	6	
Campaign 1	0.13	0.09	53	NaN	NaN	0	
Campaign 2	0.11	0.05	46	NaN	NaN	0	**>4**
Campaign 3	0.07	0.03	28	0.02	0.01	4	

We focus on the **cases U_{ref}<2m/s** (majority of data)

We start analysing **CFD results (NIGHT, isothermal conditions):**

- Campaign 1 (large LAI) and Campaign 3 (low LAI)
- For each Campaign, we performed two simulations: one for the parallel and one for the perpendicular wind (*directions represent the mode of field data*)

Results: TKE from CFD

Isothermal conditions z=4.5m (below tree crown)

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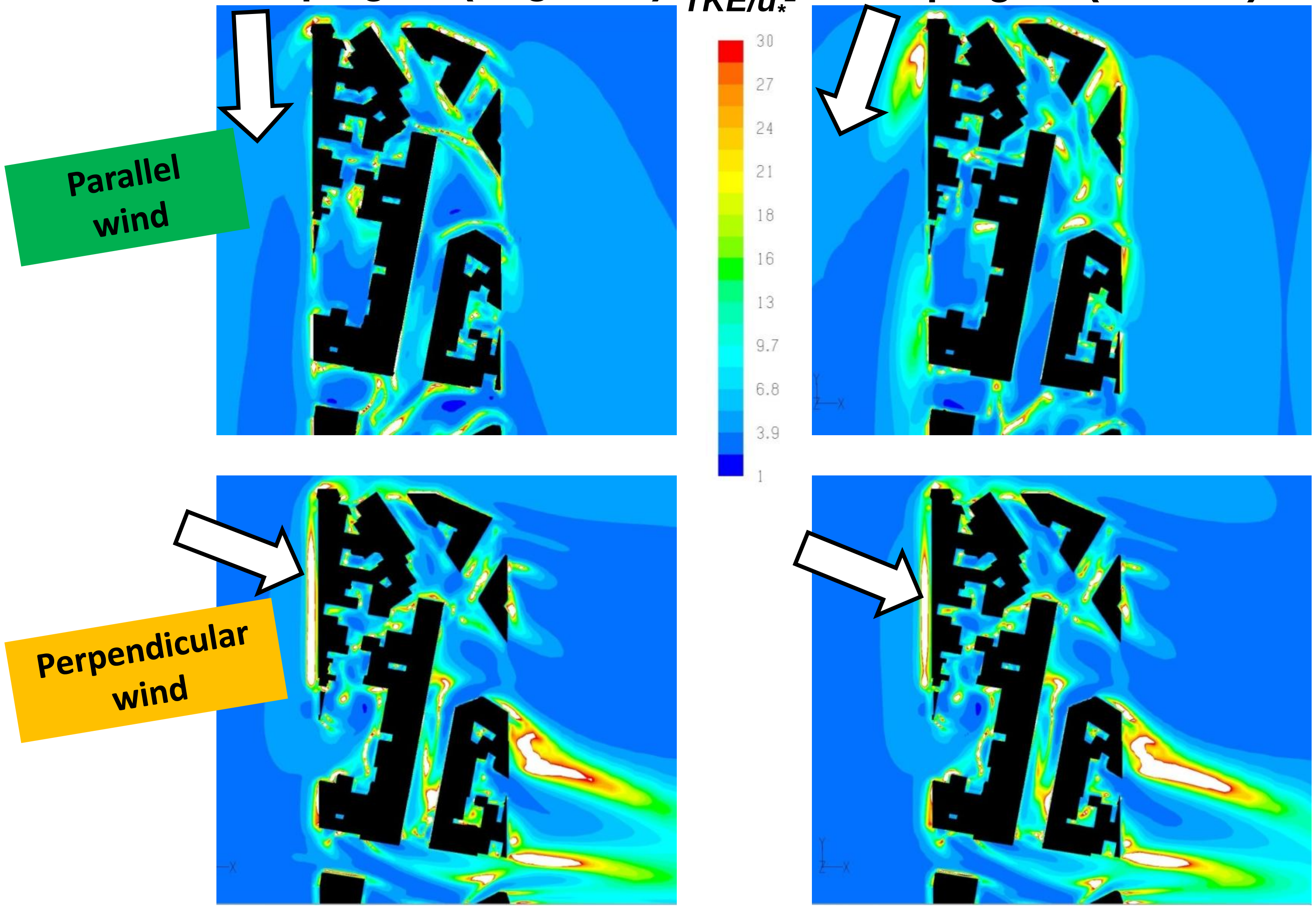
Campaign 1 (large LAI) | ***TKE/u*²*** | **Campaign 3 (low LAI)**

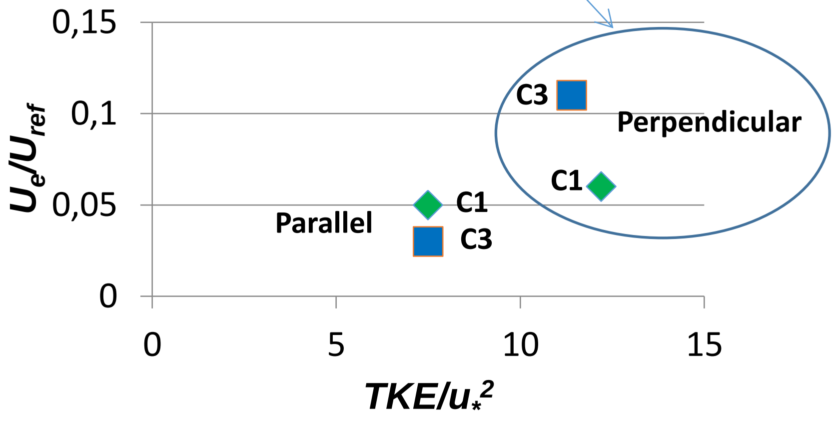


TKE

- **Slightly larger TKE for large LAI (C1)** (below tree crown). The same occurred at z=8.5m (above tree crown)
- When **averaged** over all the in-canyon volume, **no significant difference in TKE due to different LAI!**

Ue

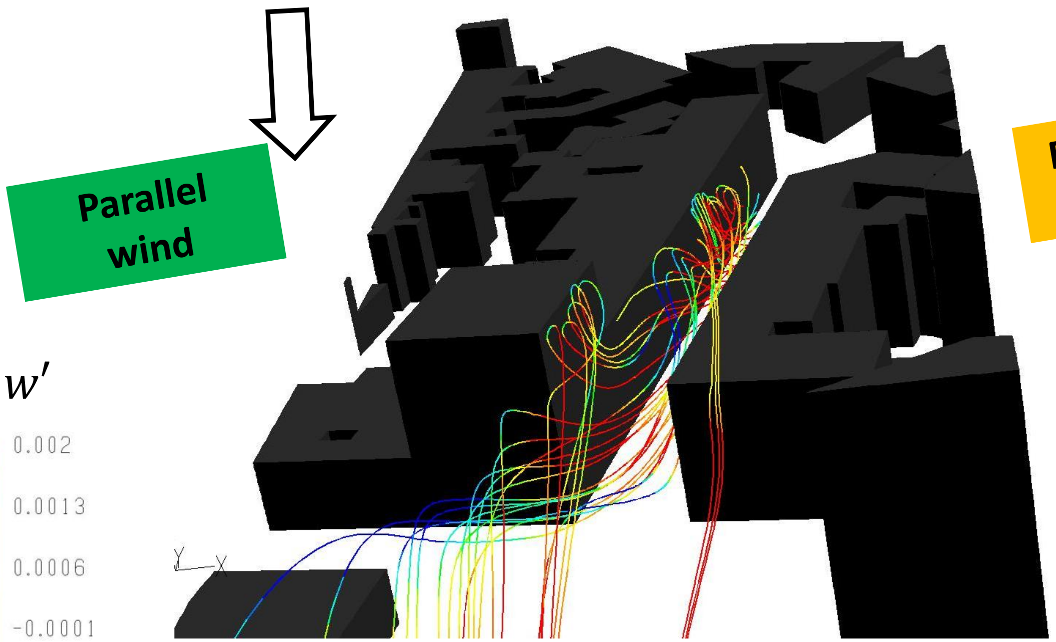
- Significant difference for different LAI especially for perpendicular wind -> **higher *Ue* for low LAI (C3)** due to lower blockage effect

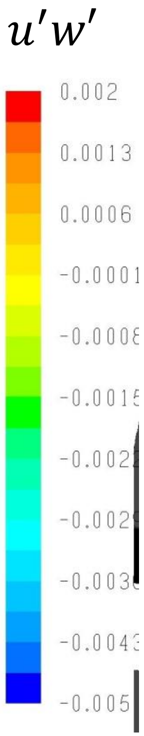


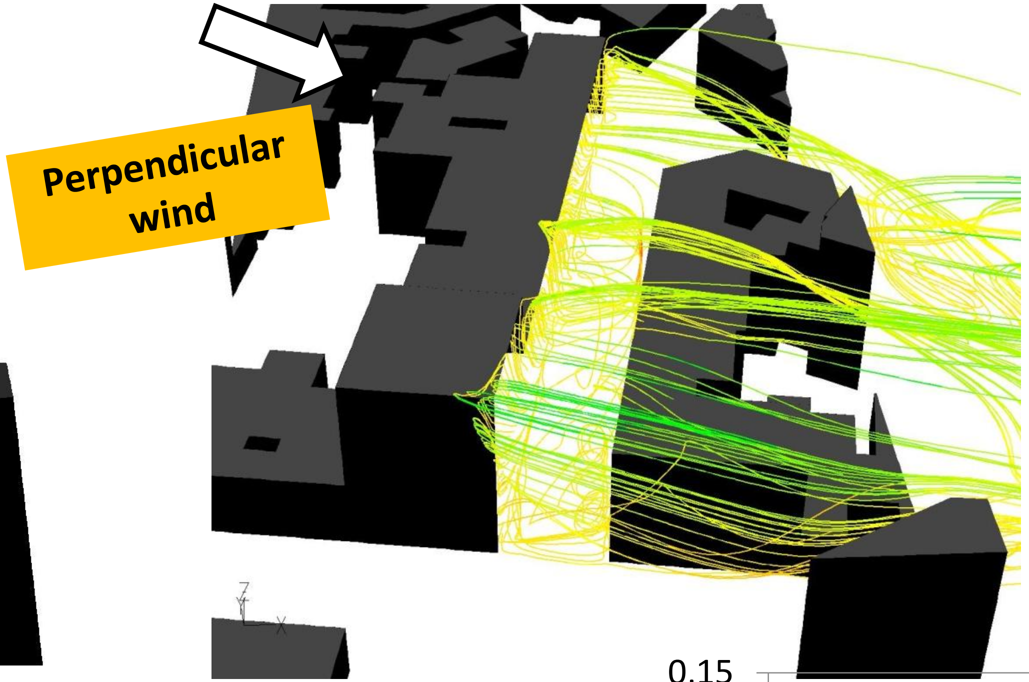
in-canyon volume averaged

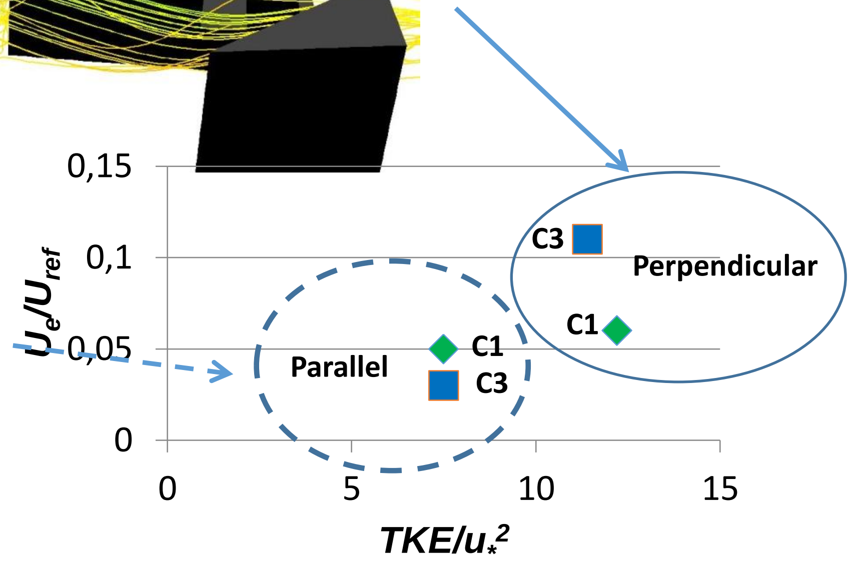
Results: Exchange velocity from CFD

Isothermal conditions









U_e

- Significant difference for different wind directions **-> higher U_e for perpendicular wind <u>especially due to the mean flow structure</u>**

in-canyon volume averaged

Results: U_e vs exchange reduced plane

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In urban canopies, the exchange area A_C is assumed constant (lenght × width of the canyon), while in our case A_C varies with crown size, leaf density, season… in other words the plane of exchange is reduced

β =reduction of the exchange plane = $(1-(A_{tree}/A_C))$

We thus estimate an effective exchange area $A_e = AC \times \beta$

if $\beta \neq 1$

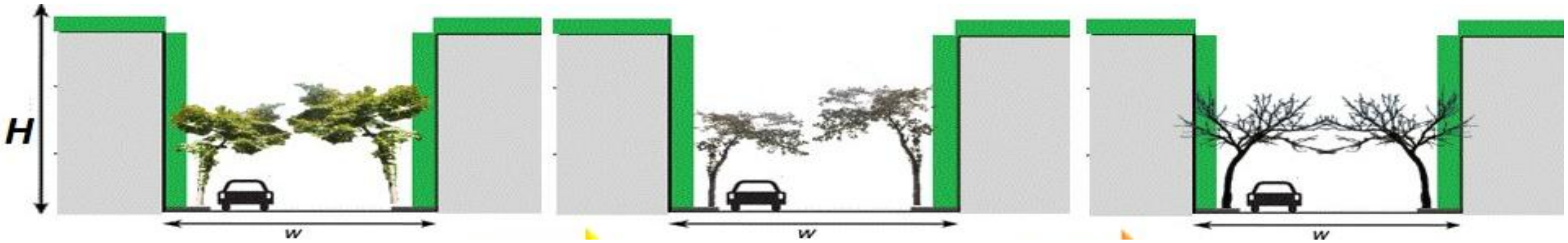
$$A_{tree} = \mathrm{LAI}\frac{r}{2W}N\pi r^2$$

r = crown radius

W = width of the canyons

N = number of trees

$$U_e = \frac{\iint(\overline{\rho u'w'} + \rho uw)dS}{\rho A_c(U_{ref} - U_c)}$$



β <<1 ($A_e \to 0$)

β intermediate

β ~1 ($A_e \to A_C$)

Results: Exchange velocity

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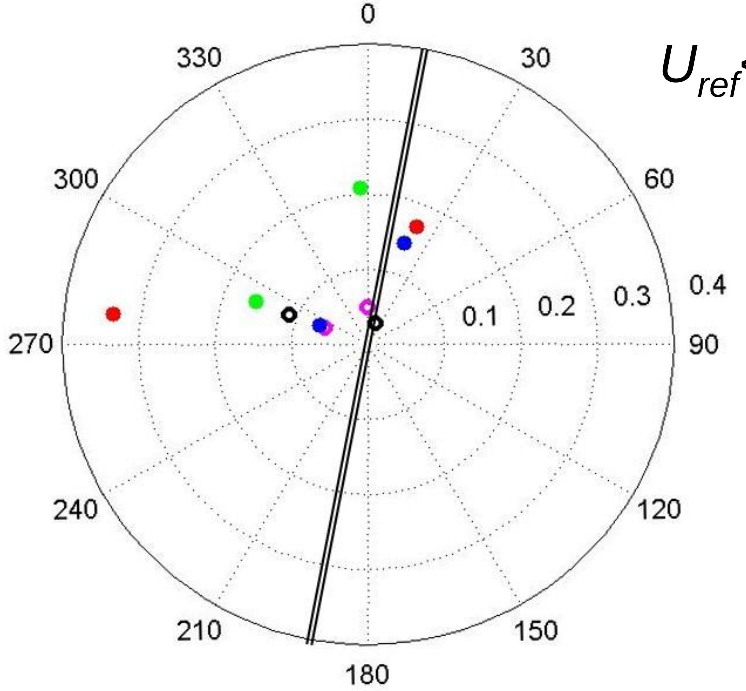
Night-time (hh. 23:00 – 05:00)



U_{ref}<2m/s

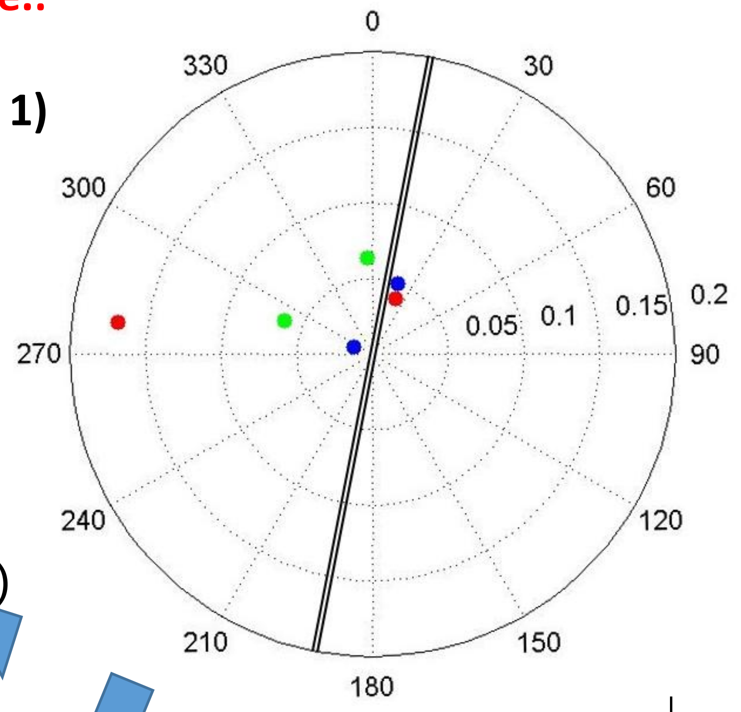
$$U_e/U_{ref} = \left|\frac{\overline{u'w'} + uw}{U_{ref}(U_{ref} - U_c)}\right|$$

- Campaign 1 – large LAI (green)
- Campaign 2 – Intermediate LAI (red)
- Campaign 3 – low LAI (dark blue)
- CFD – Campaign 1 (pink circle)
- CFD – Campaign 3 (black circle)

Field data show opposite results, i.e.:

- ***U_e* is higher for parallel wind**
- ***U_e* is higher for large LAI (Camp. 1)**

- This may imply that **the turbulent part is more important than the mean counterpart** (*the latter dominates in the CFD results*)
- We thus investigated the contribution of $\overline{u'w'}$



$$U_e/U_{ref} = \left|\frac{\overline{u'w'}}{U_{ref}(U_{ref} - U_c)}\right|$$

- We obtained the **same behaviour** as for the formulation with uw
- This implies that **for large LAI, even though there is windbreak (as shown before), *U_e* is higher due to more turbulence (probably from leaves** which the CFD does not take into account for) and thus there is a large exchange in-out of the canyon

Results: U_e vs TKE

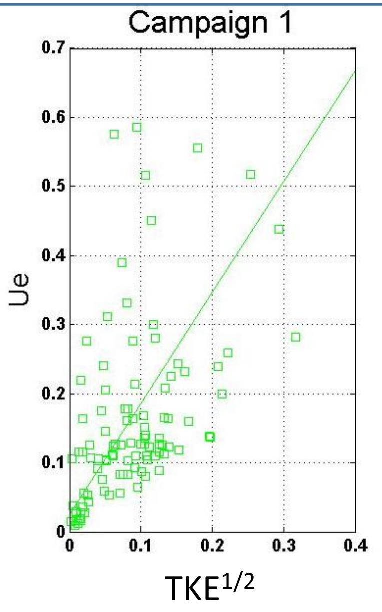
20^{th}-24^{th} July 2015 Toulouse France

Night-time (hh. 23:00 – 05:00)

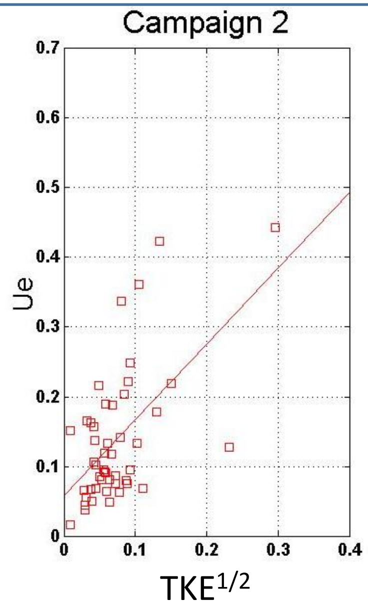
U_{ref}<2m/s

Parallel wind
WD: 11° ± 15°

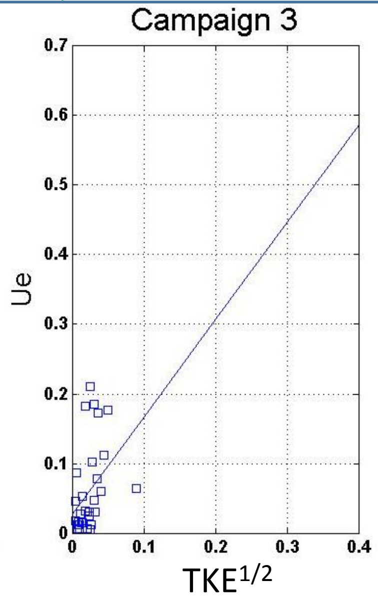
Perpendicular wind
WD: 281° ± 15°



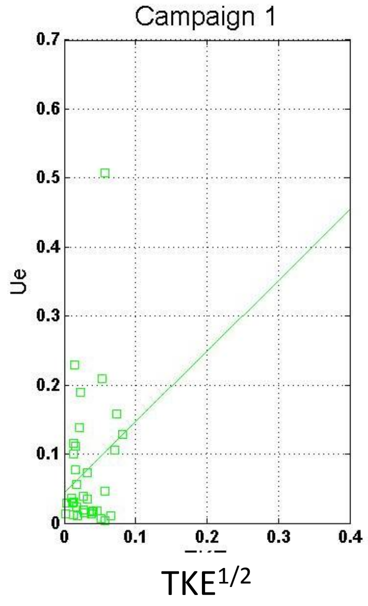
$U_e = 1.6(TKE)^{1/2} + 0.025$



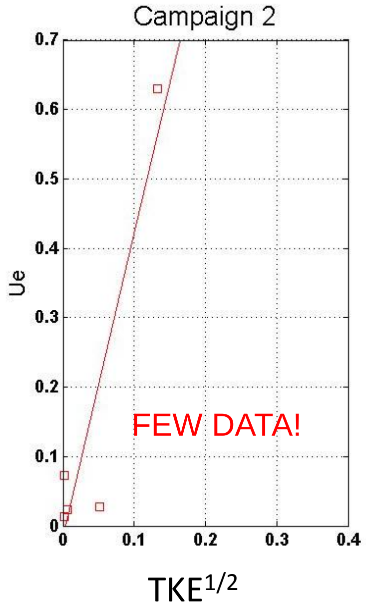
$U_e = 1.1(TKE)^{1/2} + 0.057$



$U_e = 1.4(TKE)^{1/2} + 0.027$

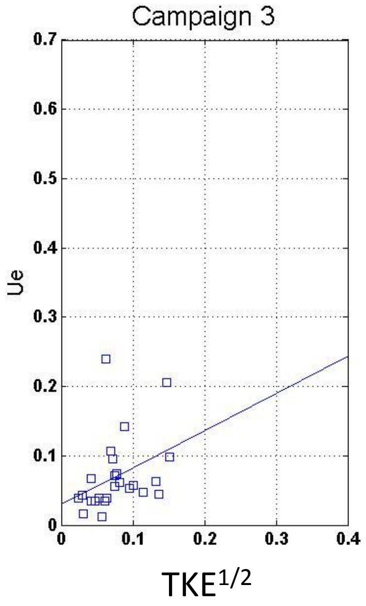


$U_e = 1(TKE)^{1/2} + 0.044$



$U_e = 4.4(TKE)^{1/2} + 0.016$

FEW DATA!



$U_e = 0.54(TKE)^{1/2} + 0.030$

Conclusions

- Using **high-frequency flow data** in combination with **CFD simulations** it has been possible to appreciate the **effect of trees on wind speed reduction and vertical turbulent exchange between a street canyon and the overlying atmosphere**

  - A significant **windbreak effect** was observed **in the street canyon with trees** (large LAI), as confirmed by simulations

  - The analysis has shown that in the real case **the effect of turbulence induced by leaves**, neglected in CFD simulations, may be predominant on the mean flow and TKE due to the whole tree crown especially in the perpendicular wind direction

  - As a consequence, **the exchange velocity U_e was found higher for the street canyon with trees (large LAI)**

  - A better parametrization of U_e is required to take into account the turbulent contribution of trees in the exchange as shown in the field measurements.

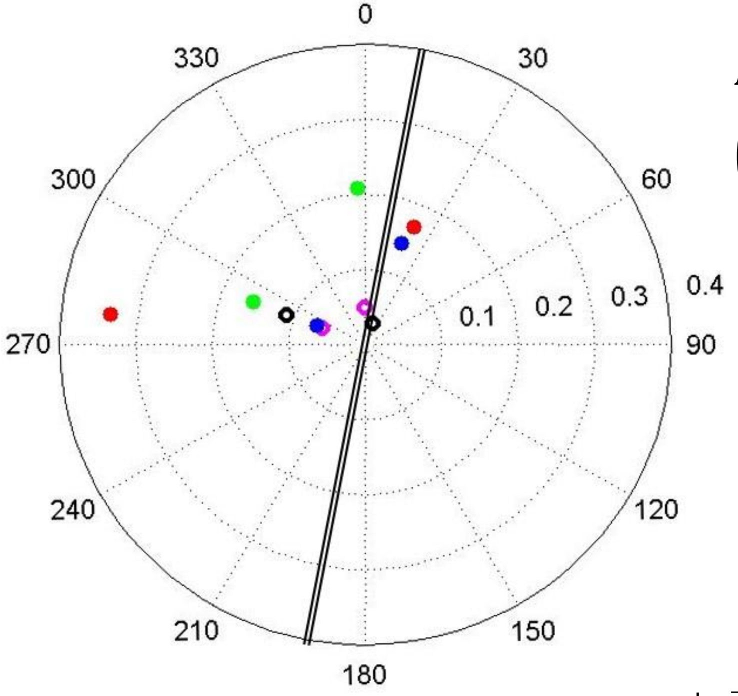
Aknowledgements

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

Results: exchange velocity

iCUC9 20th-24th July 2015 Toulouse France

Night-time (hh. 23:00 – 05:00)

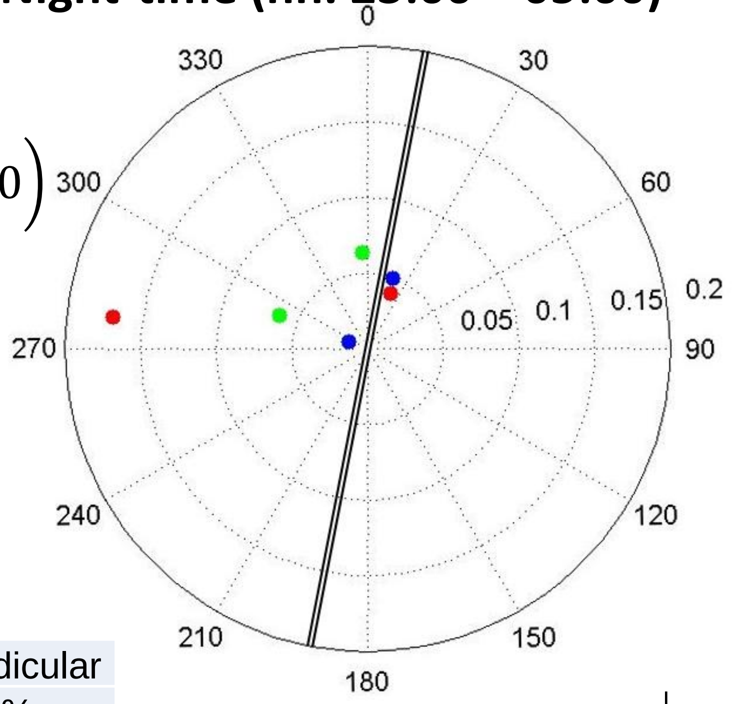


$$Percentage\ U_e/U_{ref} = \left(\frac{U_e/U_{ref}\ Campaign\ 1 - U_e/U_{ref}\ Campaign\ 3}{U_e/U_{ref}\ Campaign\ 3} \cdot 100\right)$$

Parallel	Perpendicular
46%	131%

$$U_e/U_{ref} = \left|\frac{\overline{u'w'} + uw}{U_{ref}(U_{ref} - U_c)}\right|$$

Night-time (hh. 23:00 – 05:00)



Parallel	Perpendicular
31%	361%

$$U_e/U_{ref} = \left|\frac{\overline{u'w'}}{U_{ref}(U_{ref} - U_c)}\right|$$

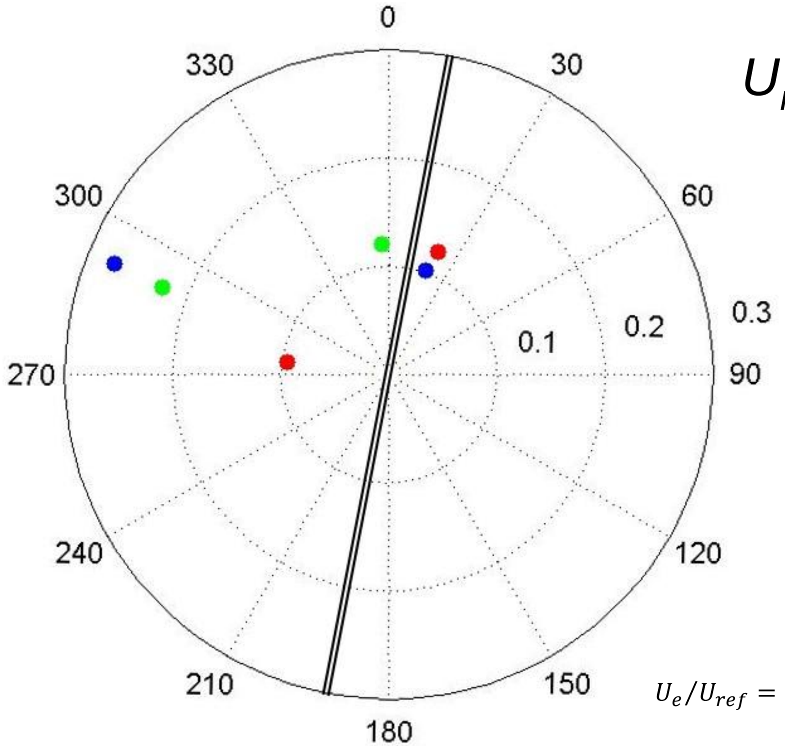
- **Campaign 1 – large LAI**
- **Campaign 2 – Intermediate LAI**
- **Campaign 3 – low LAI**
- **CFD – Campaign 1**
- **CFD – Campaign 3**

The tables show the percentage increase of the exchange for large LAI (Campaign 1) with respect to the low LAI (Campaign 3)

Results: Exchange velocity

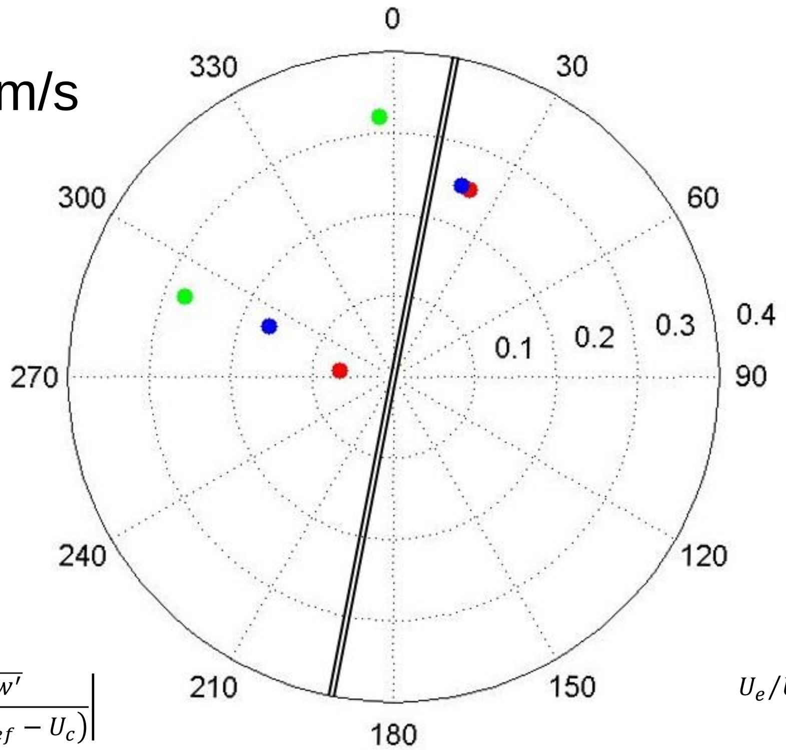
20th-24th July 2015 Toulouse France

Day-time (hh. 11:00 – 15:00)



$$U_e/U_{ref} = \left| \frac{\overline{u'w'}}{U_{ref}(U_{ref} - U_c)} \right|$$

U_{ref}<2m/s



$$U_e/U_{ref} = \left| \frac{\overline{u'w'} + uw}{U_{ref}(U_{ref} - U_c)} \right|$$

- **Campaign 1 – large LAI** (green)
- **Campaign 2 – Intermediate LAI** (red)
- **Campaign 3 – low LAI** (blue)

- The same during the day-time
- We have to investigate more the effect of buyancy