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Wake flows characteristics and merging behind tall building clusters

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Contents

Clusters of cylinders and tall buildings

- Slender engineering structures are frequently seen in groups, for example high-rise buildings.
- The simplest configuration of multiple structures is two side by side cylindrical structures which has been studied extensively (see references).
- Few studies have considered a cluster of 2x2 square cylinders at very low or subcritical Reynolds number (see references)
- Cluster of four square cylinders create much more complex flow field due to the asymmetric vortices shed by each cylinder and the presence of pulsating jet along-wind spacing.
- To understand the scaling of the dominant vortex shedding frequency for a cluster of 2x2 cylinders in FST.
- To understand the scaling of the wake flow behind a cluster of tall buildings

City of London
(available from: http://www.workspace.co.uk)

References: Alam et al., 2002, 2011, Agrawal et al., 2006, Sau et al., 2007, Burattini and Agrawal, 2013, Abbasi et al., 2014, Liu et al., 2015, Song et al., 2017, Zhang et al., 2019, Shahab et al., 2021).

LES and Governing Equations

- The LES embedded in PALM was used which is a parallelized LES model for the atmospheric boundary layer (Raasch and Etling, 1991, 1998).
- PALM solves the following filtered, incompressible Navier-Stokes equations:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{u}_i \bar{u}_j\right) = -\frac{\partial \bar{p}}{\rho \partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial \bar{u}_i}{\partial x_j}\right) + \frac{\partial \tau_{ij}}{\partial x_j}$$

Where u_i and $\bar{p}$ are the filtered velocity and pressure respectively, ρ is the density and ν is the kinematic viscosity. The kinematic sub-grid scale (SGS) stresses $\tau_{ij}$are modelled using the Boussinesq assumption,

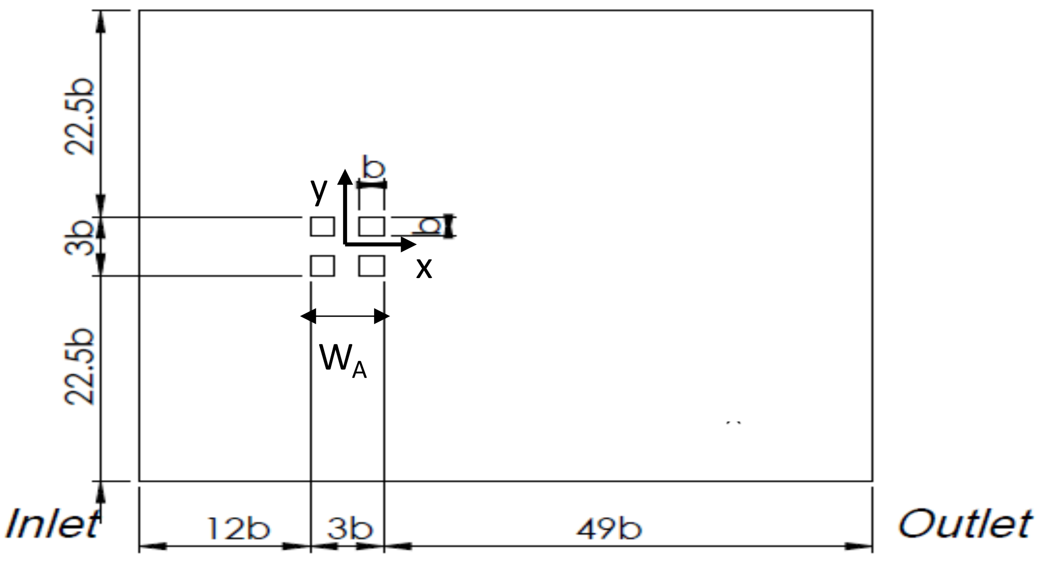
$$\tau_{ij} = \bar{u}_i \bar{u}_j - \overline{u_i u_j} = 2\nu_t \overline{S_{ij}} - \frac{1}{3}\delta_{ij}\tau_{kk}$$

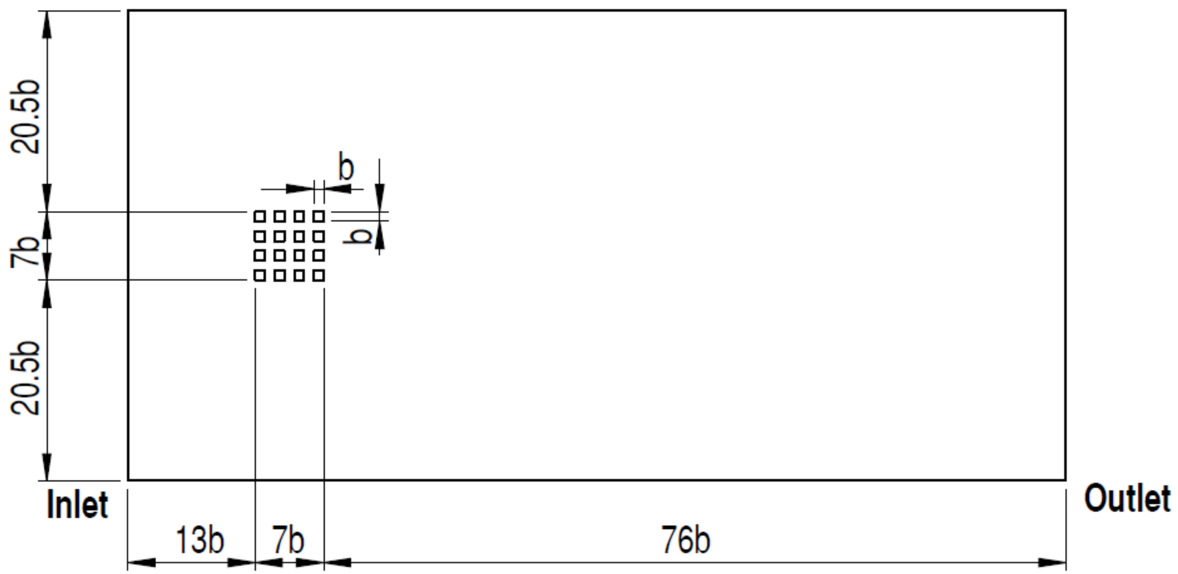
In which δ_{ij}, ν_{sgs} and $\overline{S_{ij}}$ are the delta Kronecker, the kinematic SGS viscosity and the rate-of-strain tensor for the resolved scales, respectively.

K-equation SGS model was used in PALM.

Computational Setup

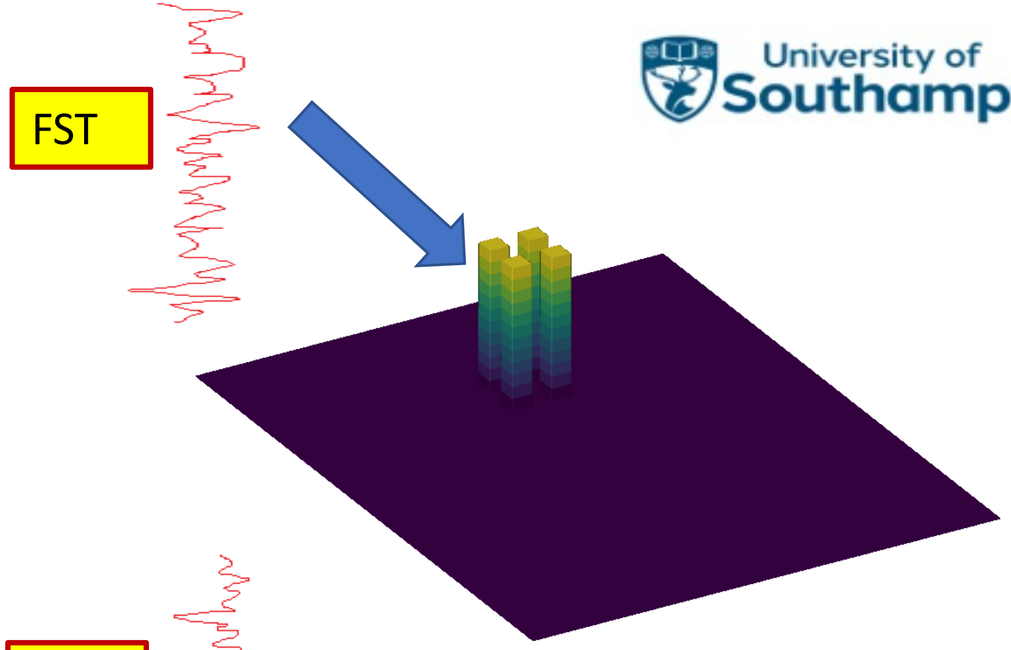
Case#	*Cluster Size*	*Domain Size*	*Mesh Size (cells)*	*Spacing between buildings*	*Array Width (W_A)*	*height in homogeneous direction*
1	*2x2*	*64bx48bx16b*	*0.8 billion*	*b*	*3b*	*16b*
	-	*-*		*-*	*-*	*Building height*
2	*4x4*	*96bx48bx16b*	*0.8 billion*	*0.5b*	*5.5b*	*4b*
3	*4x4*	*96bx48bx16b*	*0.8 billion*	*b*	*7b*	*4b*
4	*4x4*	*96bx48bx16b*	*0.8 billion*	*3b*	*13b*	*4b*

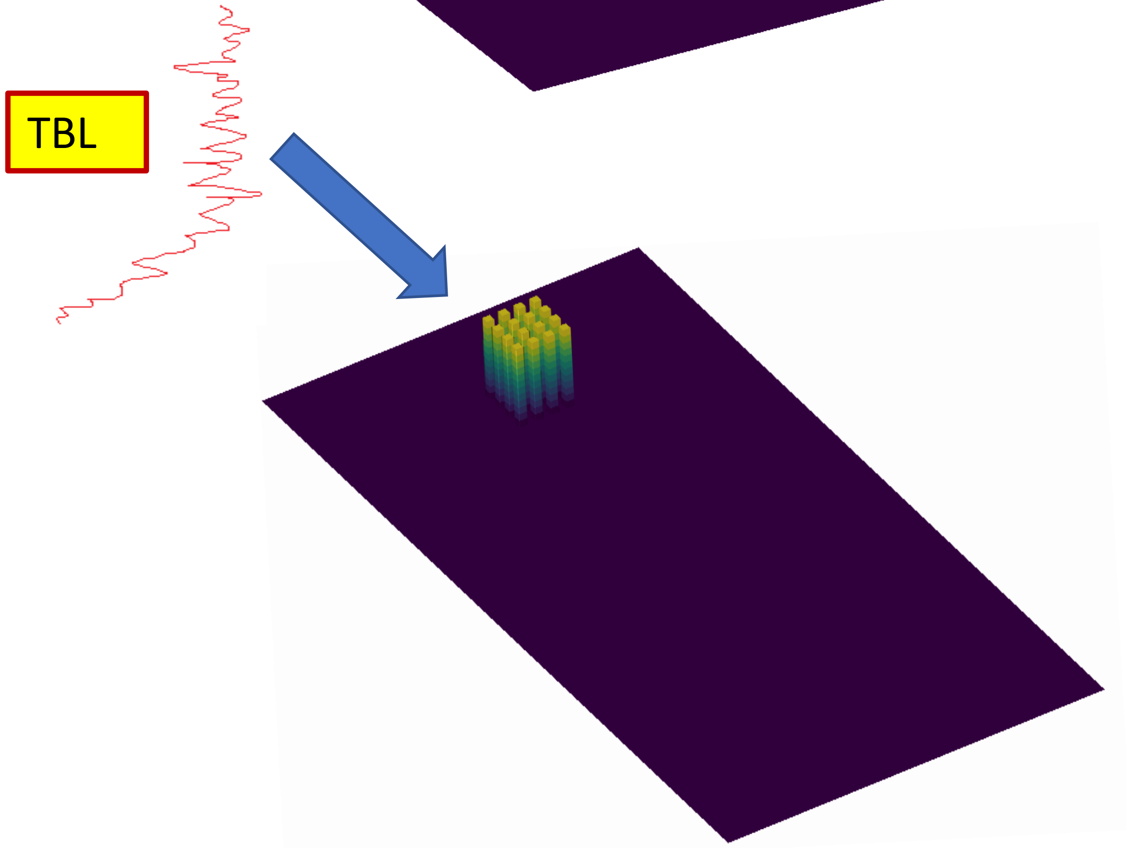




Location	*Boundary Condition*
Inlet	*Synthetic Turb (Xie &Castro 2008)*
Outlet	*Zero gradient*
Lateral	*Periodic*
Top	*Stress-free*
Bottom	*No-slip*

Geometry	*Cluster size*	*Inflow Condition*	*Integral Length Scales* $(L_x\ L_y\ L_z)$
Square cylinders	*2x2*	*FST*	*b b b* *2b 2b 2b* *3b 3b 3b* *4b 4b 4b*
Buildings	*4x4*	*Boundary layer*	*4b b b*





A 2x2 square cylinder cluster in smooth and FST flows

Wavelet Analysis

- The conventional Fourier can struggle to identify energetic and localised events in time series.
- The wavelet analysis has the ability to capture local-time spectra of a signal and can be used for identifying multiple scales in wake flows.
- The wavelet transformation of a time series signal ξ(τ) (e.g. a time series of the wake velocity or the aerodynamic force acting on an individual cylinder) is defined as follows:

$$T_p(a,t) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} \psi^* \left(\frac{\tau - t}{a}\right) \xi(\tau) d\tau$$

where T_p is the wavelet coefficient, ψ is the mother wavelet with the asterisk denoting the complex conjugate of the function, and a and t are respectively the scale and translation parameters.

For a clear identification of the energetic scales, the mean wavelet magnitude is used

$$\bar{S}(\tilde{n}) = \int_{-\infty}^{\infty} \left|T_p(\tilde{n}, t)\right| dt$$

Where $\tilde{n} = {}^{fl}/_{U_\infty}$ is dimensionless frequency. For vortex shedding frequency, $\tilde{n}$ is commonly referred to as Strouhal number St. The time-average wavelet magnitude $\bar{S}(\tilde{n})$ is calculated from the integration over the entire time duration of the wavelet coefficient.

Probe Locations

	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
x/b	4.75	4.75	6.75	6.5	9.5	15	16.75	18.75
y/b	6.25	9.25	9.25	12.75	12.75	19.25	19.25	19.25

Locations of the velocity probes placed in the near and far wake region.

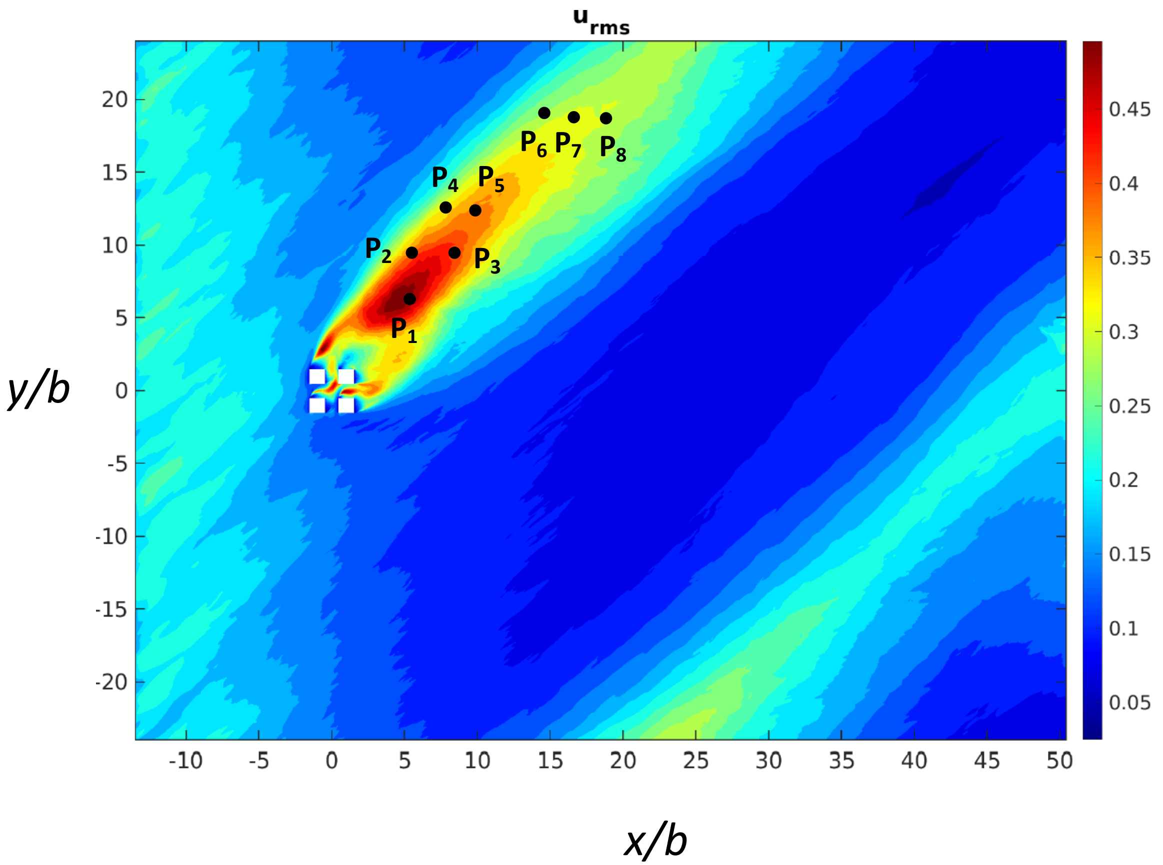


Figure 1: Time-averaged streamwise rms velocity contours for a cluster of 2 × 2 infinite-height cylinders at half height.

Wavelet Analysis for α = 45°   (smooth inflow)

- The time-frequency scalogram map shows a dominant frequency $\tilde{n} = 0.054$ for α = 45°.
- This dominant frequency is very close to half of the dominant frequency $\tilde{n} = 0.106$ for an isolated cylinder (Mueller, 2012).
- This confirms that the cluster at α = 45° behaves as it was an individual isolated cylinder with width equal to 2b.

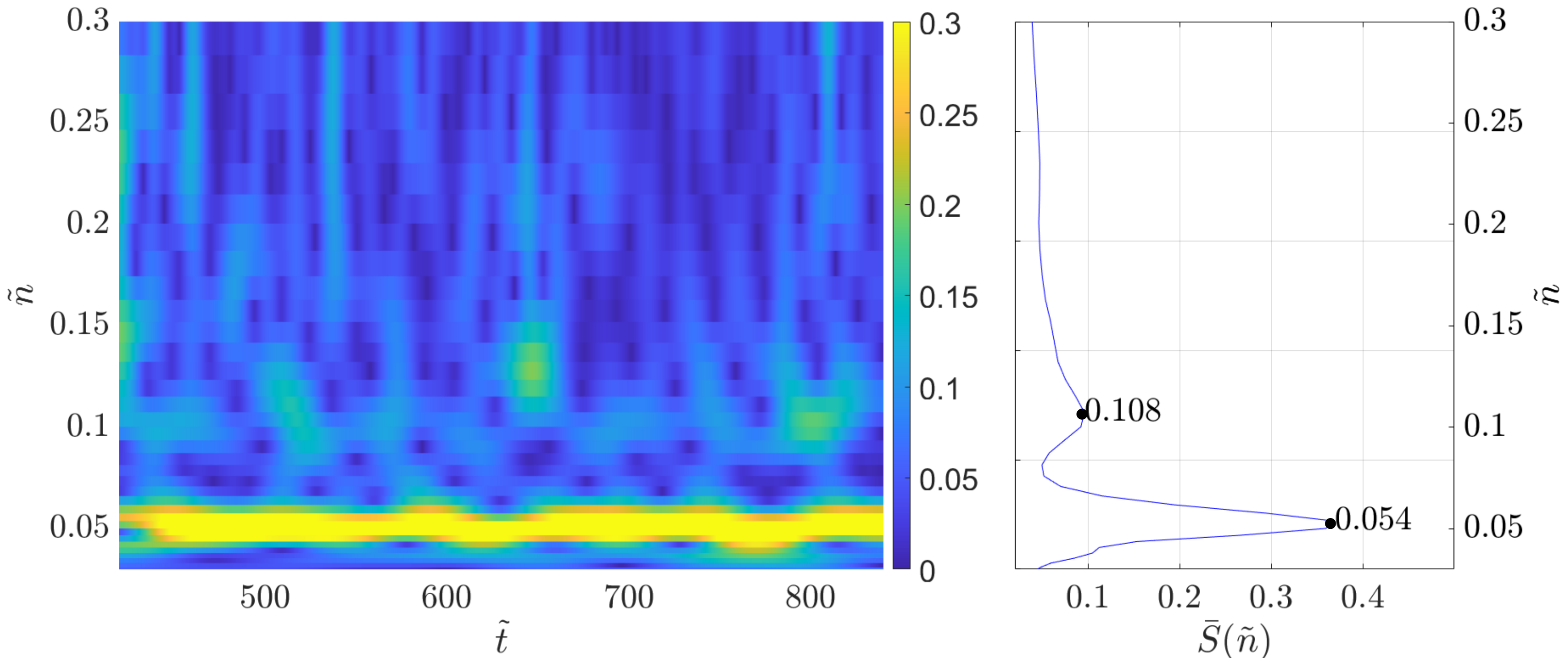


Figure 2: Time-frequency scalogram map (left) and the time-averaged wavelet magnitude of the streamwise fluctuating velocity at location P_7 at α = 45°

Wavelet Analysis for α = 45° (Turbulent Flow)

- The dominant shedding frequencies are:

$$\tilde{n} = 0.054 \text{ (smooth)}, \tilde{n} = 0.050 \text{ (Lx,y,z=1b,2b)}, \tilde{n} = 0.047 \text{ (Lx,y,z=3b,4b)}.$$

- This suggest that by increasing the free-stream length scale equal to or greater than the cluster size i.e., 3*b*, the value of the dominant shedding frequency *St* is evidently reduced by up to 13%.

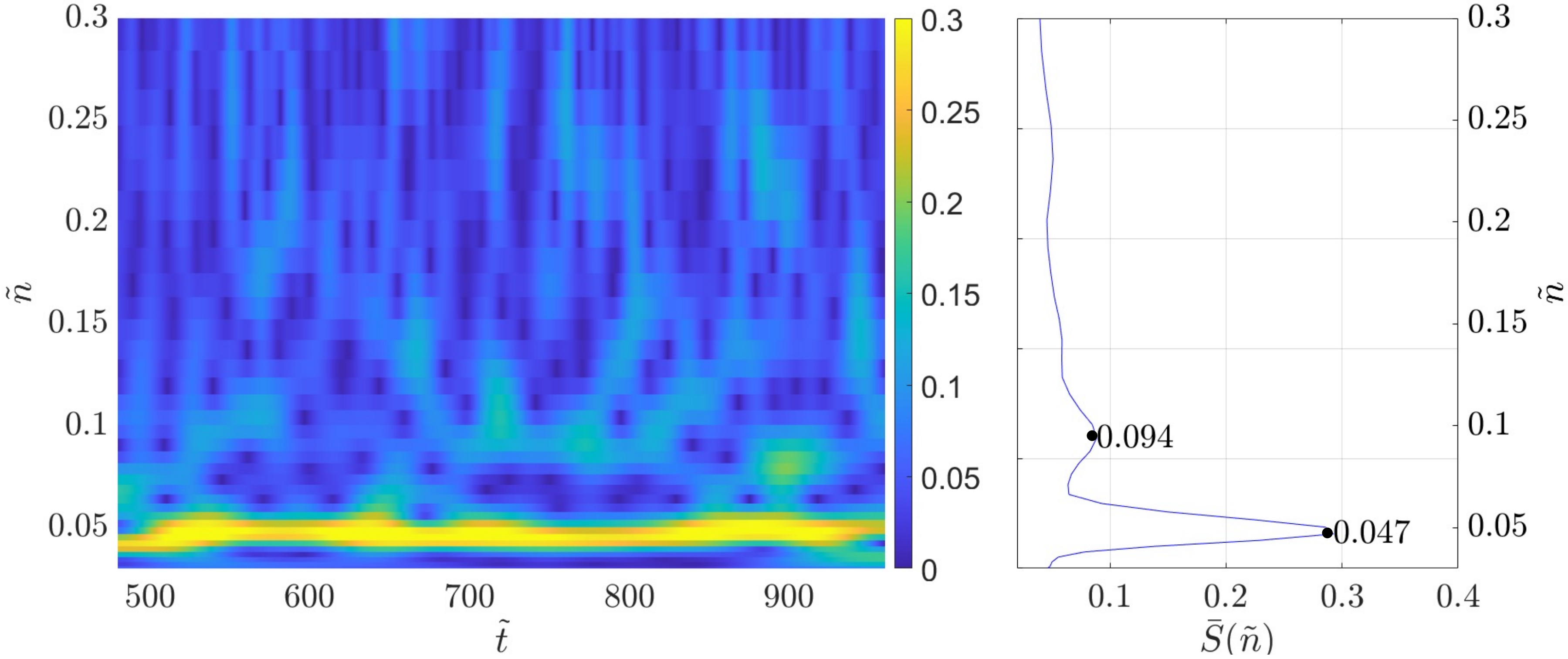


Figure 3: Time-frequency scalogram map (left) and the time-averaged wavelet magnitude of the streamwise fluctuating velocity in far wake at P_8 at α = 45°

A 4X4 finite-height cluster in boundary layer flow

Contours of Mean Streamwise Velocity at half height

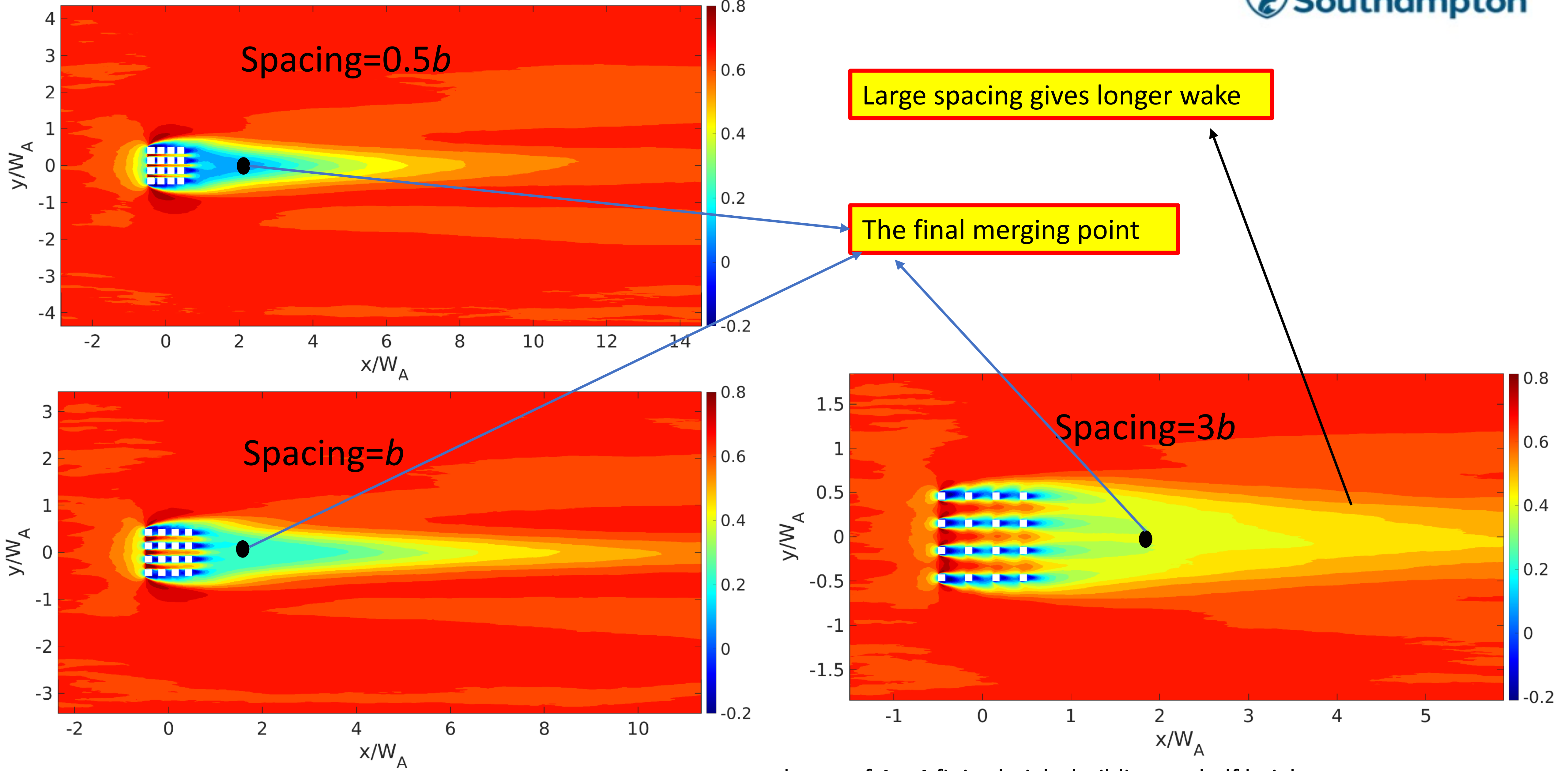
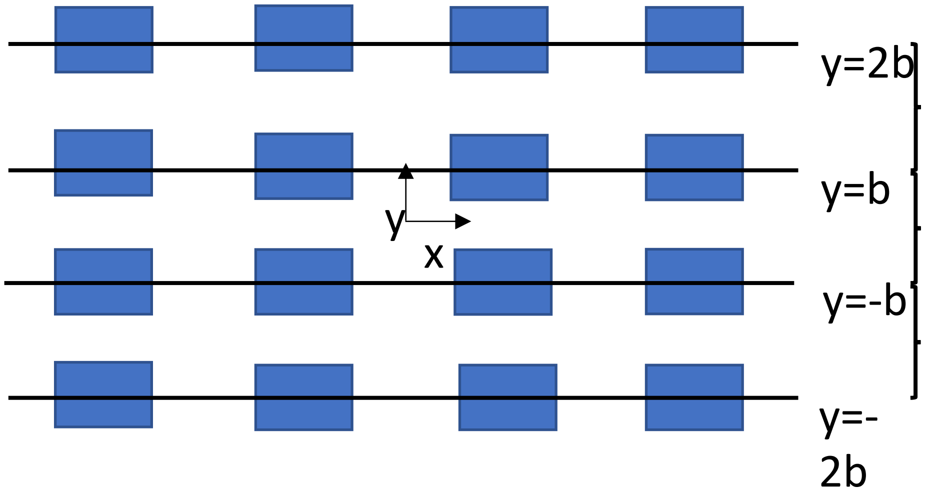
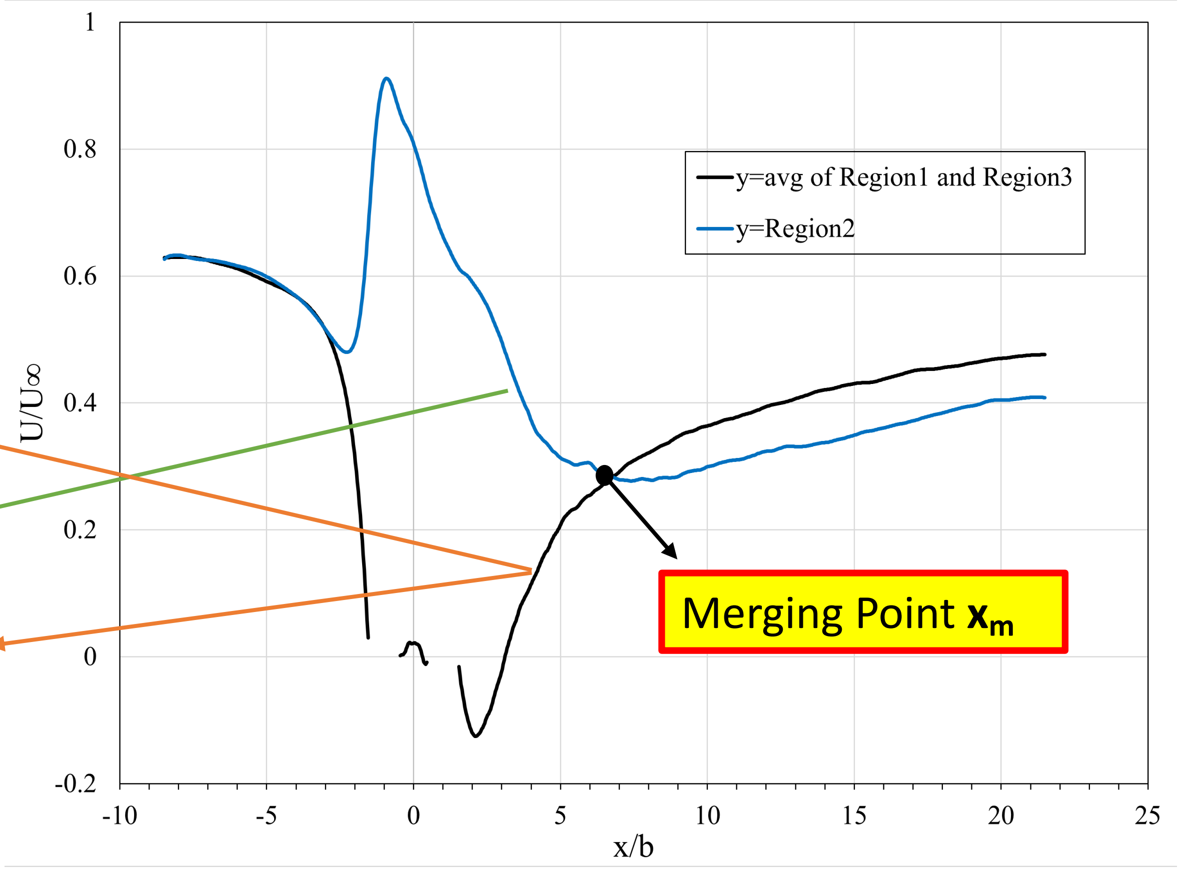


Figure 4: Time-averaged streamwise velocity contours for a cluster of 4 × 4 finite-height buildings at half height.

Merging of Wakes for 4x4 Cluster

- Local Averaging across three regions.
- After local averaging, the final velocity profiles of Region 1 and Region 3 were averaged and plotted against the velocity profile of Region 2.





Effect of spacing on the wakes merging location

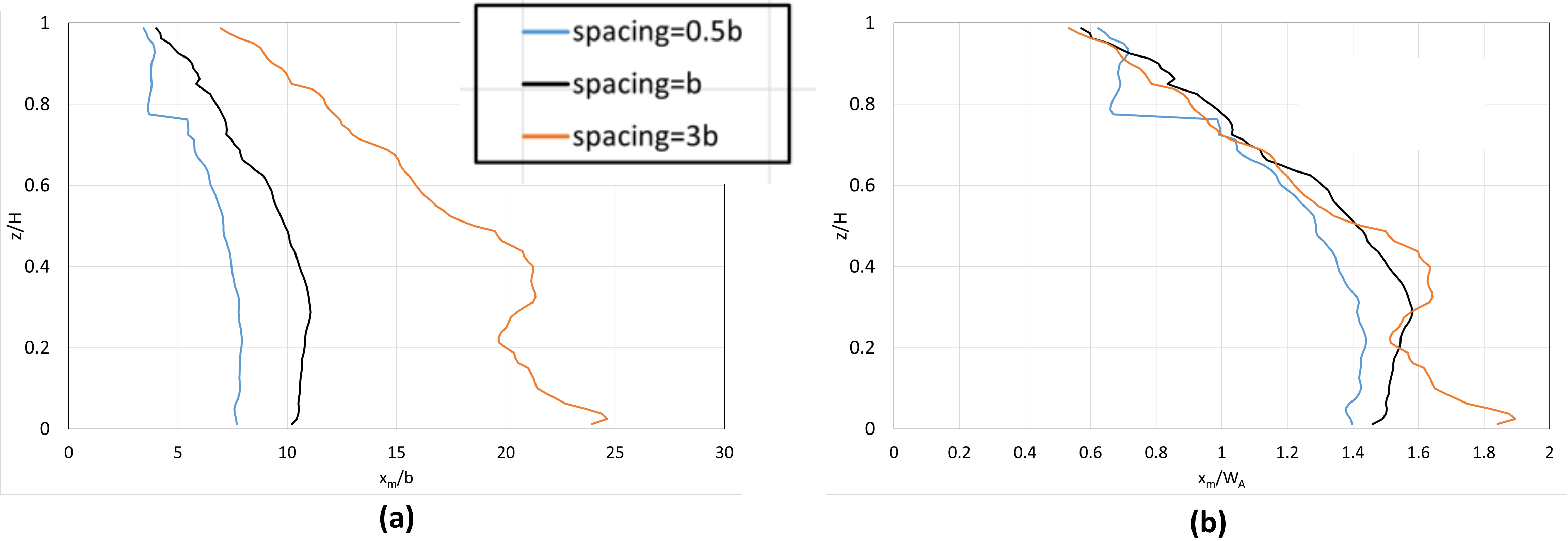


Fig.6: The downstream distance of the merging point from the centre of cluster normalised by a) building width ***b*** b) cluster width $\mathbf{W_A}$

Building width=*b*=60m

W_A for spacing 0.5*b*=5.5*b* (330m)
W_A for spacing *b*=7*b* (420m)
W_A for spacing 3*b*=13*b* (780m)

The final merging distance of wakes for 4x4 cluster with different spacing scales with cluster width W_A

Conclusion and Panned work

- For the incoming smooth flow, the frequency of the shed vortex from the 2x2 cylinder cluster can be scaled by cluster size 2*b* *(see more from the Poster).*

- Free-Stream Turbulence reduces the shedding frequency by up to 13%.

- Increasing the free-stream length scale equal to or greater than the cluster size reduces the value of normalised dominant shedding frequency.

- The final merging distance of the far wake for 4x4 tall building cluster with various spacing can be scaled by the cluster width.

- Future work would focus on checking whether the dimensionless dominant shedding frequency for clusters of 4x4 and 8x8 square cylinders is scaled by the cluster size i.e., 4*b* and 8*b* respectively.

LES for CoL

- Will use the same WT model, this will be the focus of the real urban geometry

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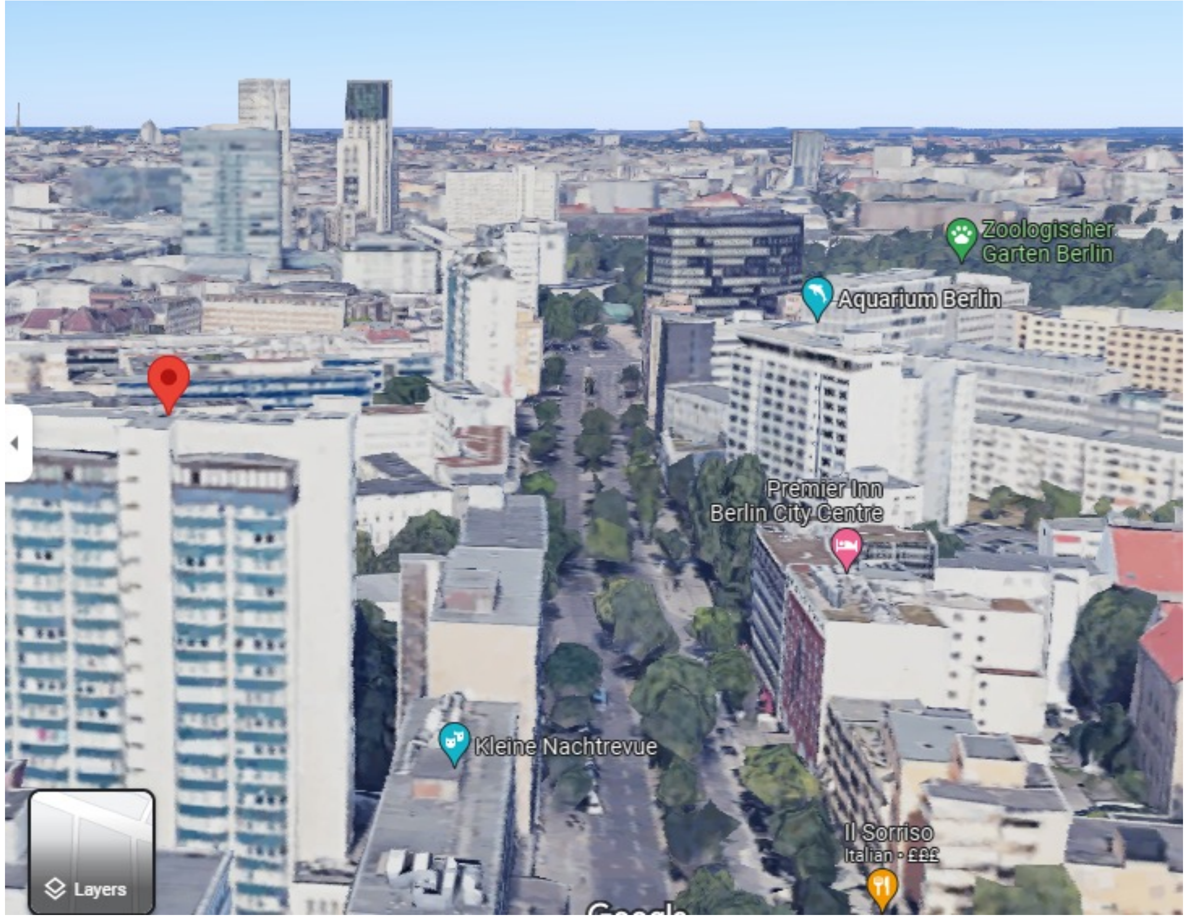
LES for Berlin



- Will simulate several typical wind direction cases for the Berlin field experiment campaign. (Prof Janet Barlow will give more details)

THANK YOU!