A formulation for the street canyon Recirculation Zone, based on parametric analysis of Large Eddy Simulations

Arsenios Chatzimichailidis[1], Christos D. Argyropoulos[2], Marc Assael[1], Konstantinos Kakosimos[2]

[1]Department of Chemical Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece

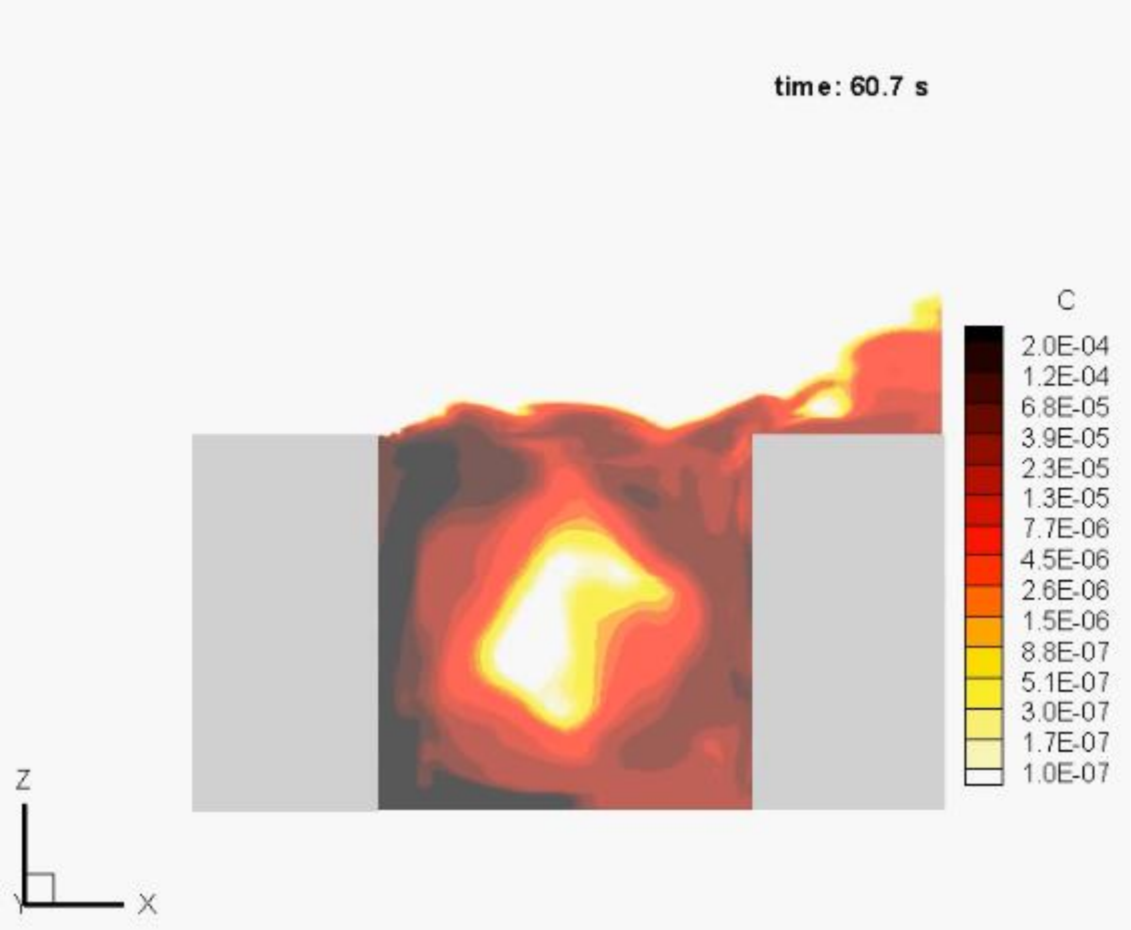
[2]Chemical Engineering Department & Mary Cay ‘O Connor Process Safety Center, Texas A&M University at Qatar, Doha, Qatar

18th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes

Outline

1. Motivation
2. Hypothesis
3. Background
4. Methodology
5. Results
6. Discussion
7. Future work

1. Motivation: Dispersion modelling

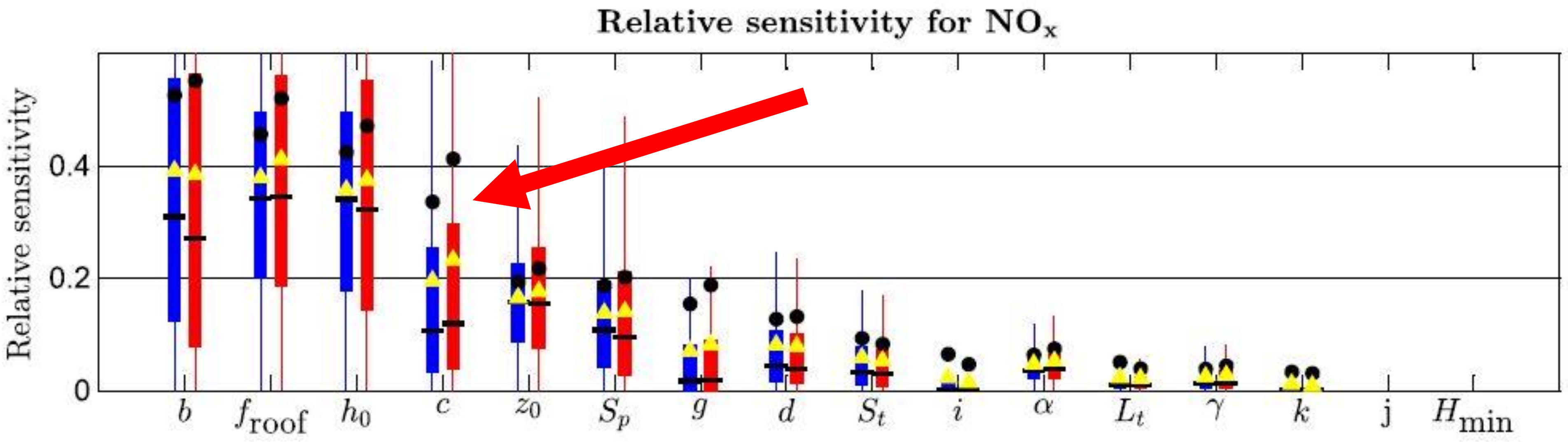


- Dynamic exposure to pollutants
  - ➢ High spatial and temporal resolution of concentrations
  - ➢ Fast operational dispersion models
  - ➢ Capture the pollution hotspots and their variability
- Improve the operation street pollution modelling
- Using LES to generate appropriate developing datasets

2. Hypothesis

Mathematical model

- Each model uses different parameterisations
- Local sensitivity analysis for OSPM (Ottosen et. al., 2016)



- Recirculation zone ➔ 4th most influential parameter

2. Hypothesis

- Is there any quasi-universal expression for the “recirculation zone”, that could expand the applicability of the typical street canyon models?

- The goals are to study the recirculation zone formation
  - in irregular street canyons
  - in arbitrary wind direction
  - variable meteorology
  - scale of street canyons

- Not intended to repeat the flow pattern study in street canyons, but improve the approach in empirical models.

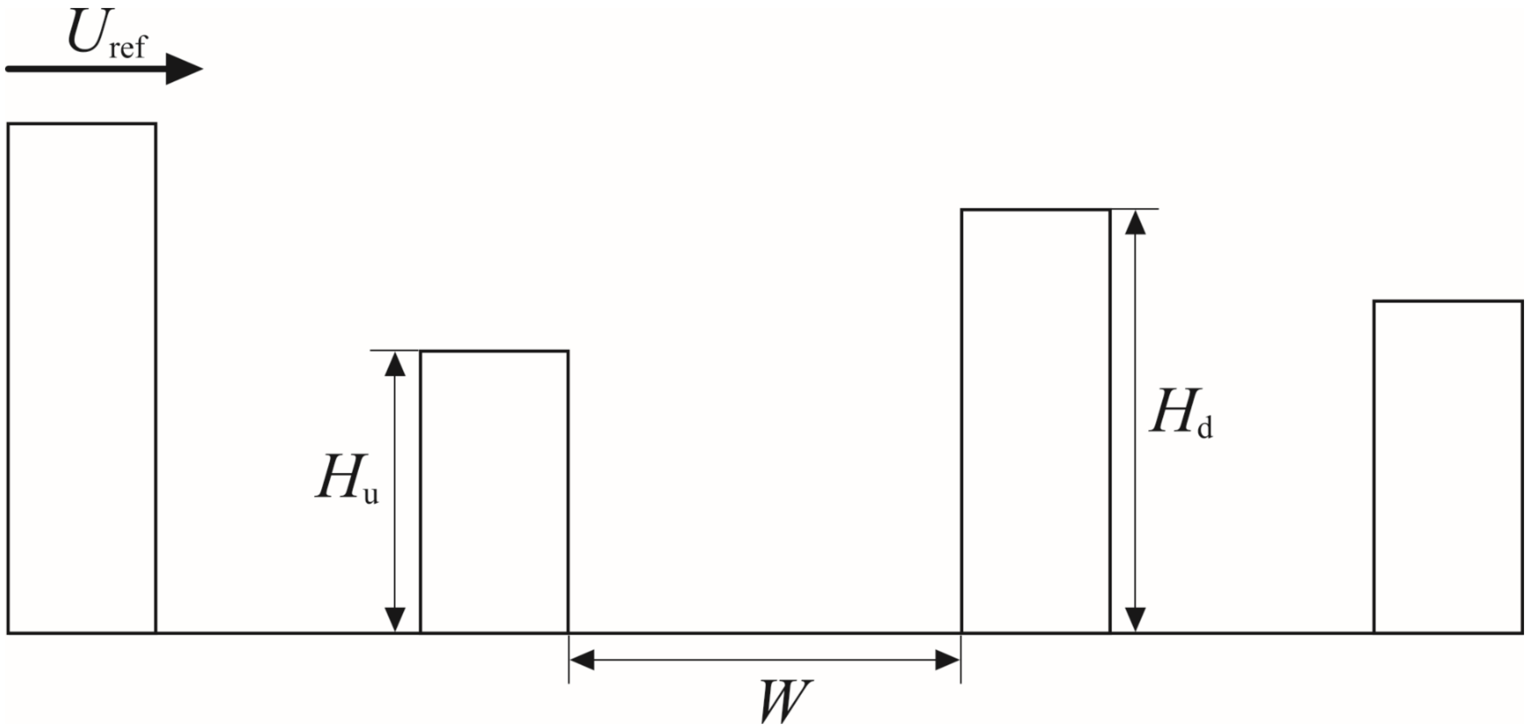
3. Background: Physical parameters

Street canyon Air Quality Models

Geometry + Meteorology ➔ Mathematical model

Physical parameters

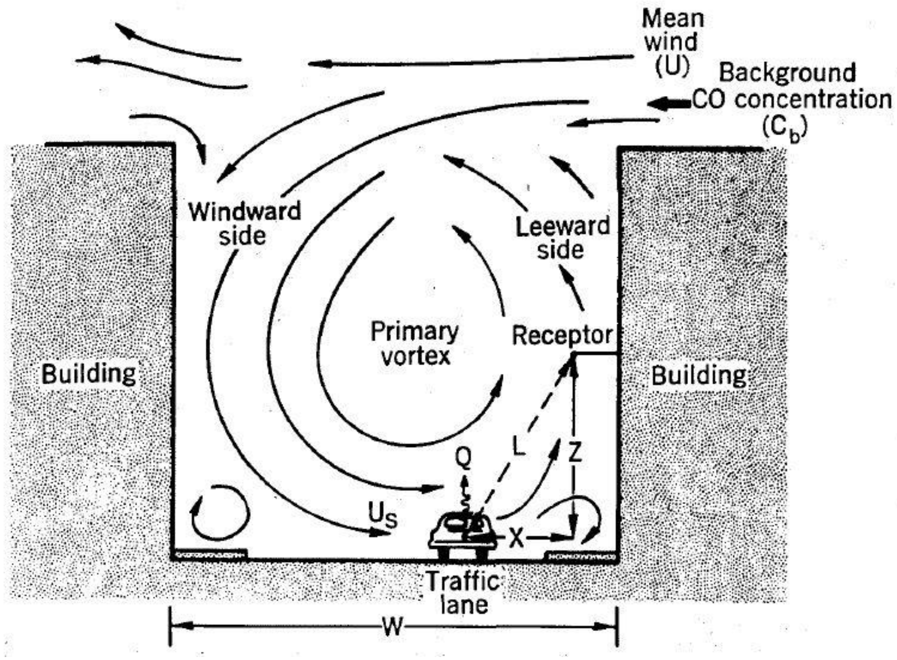
- Street canyon geometry
  - ➢Aspect ratio
  - ➢Building height ratio
  - ➢High buildings
- Wind direction and speed
- Solar radiation
- Source location and rate



3. Background: Modelling of recirculation

Upwind and downwind sides have unequal concentrations

- STREET-SRI (Johnson et al., 1973)



- Two equations for the two road sides

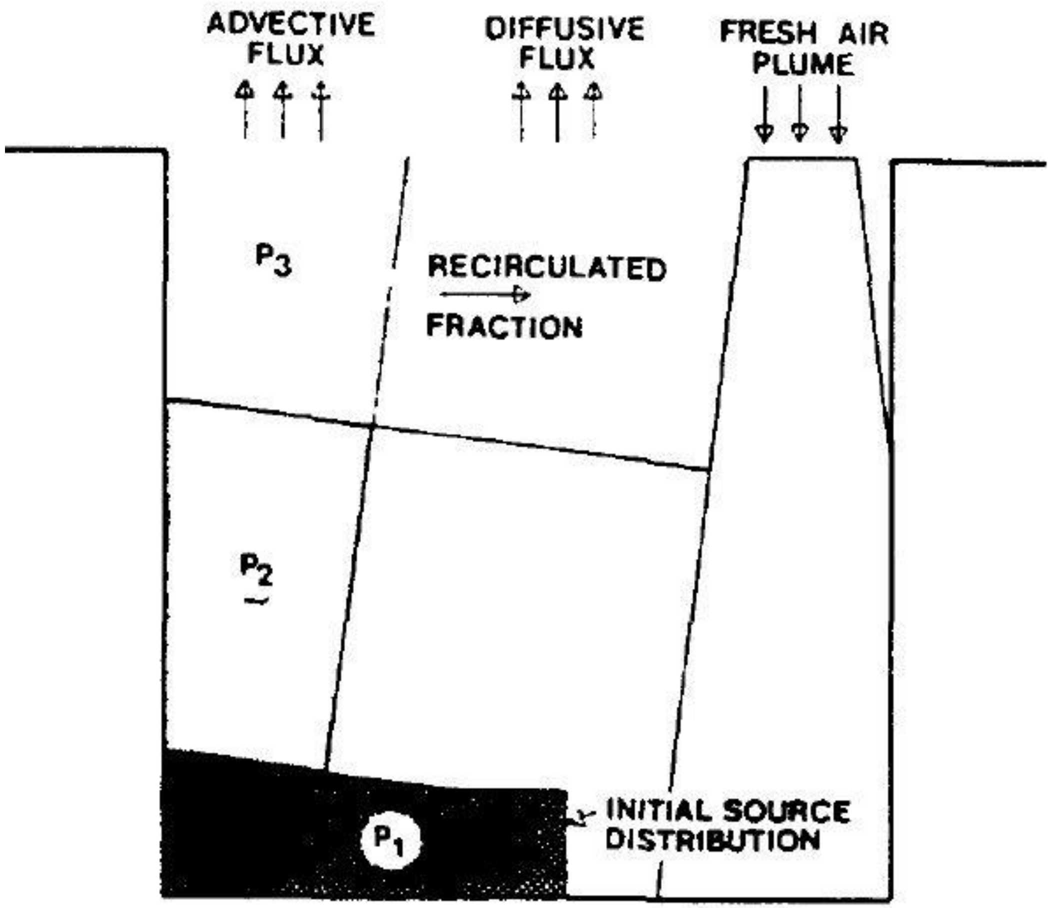
$$\Delta C_L = \frac{0.07N}{(U + 0.5)[(x^2 + z^2)^{1/2} + 2]}$$

$$\Delta C_W = \frac{0.07N}{W(U + 0.5)}$$

- Parameters calibrated, using field data
- Implicit modelling of the recirculation

3. Background: Modelling of recirculation

- CPBM (Yamartino and Wiegand, 1986)



- Two equations for the two road sides

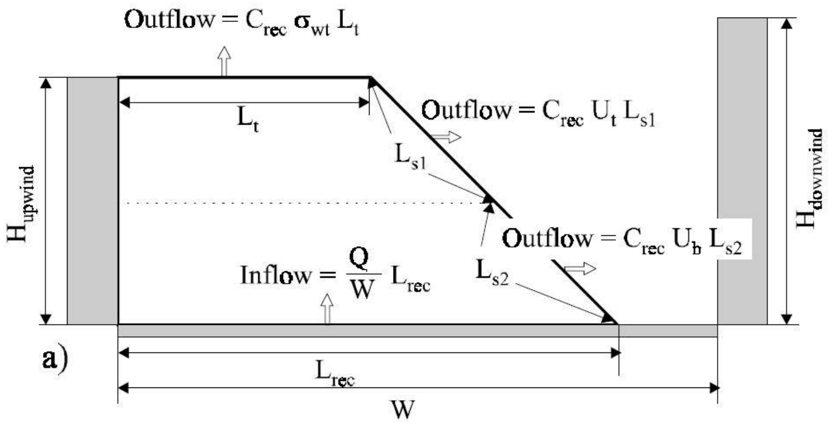
$$C_{lee} = C_b + \frac{Kq}{(u+u_o)[(x^2+z^2)^{1/2}+L_o]}$$

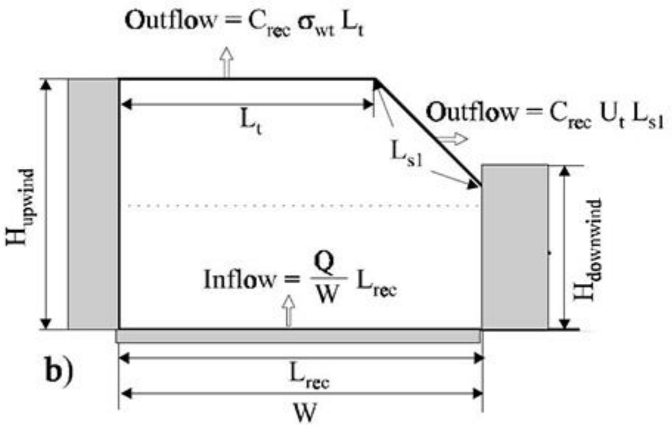
$$C_{luv} = C_b + \frac{Kq(H-z)}{(u+u_o)HB}$$

- Three characteristic regions
- Parameters calibrated, using field data
- Implicit modelling of the recirculation

3. Background: Modelling of recirculation

- OSPM (Berkowicz et al., 1997)

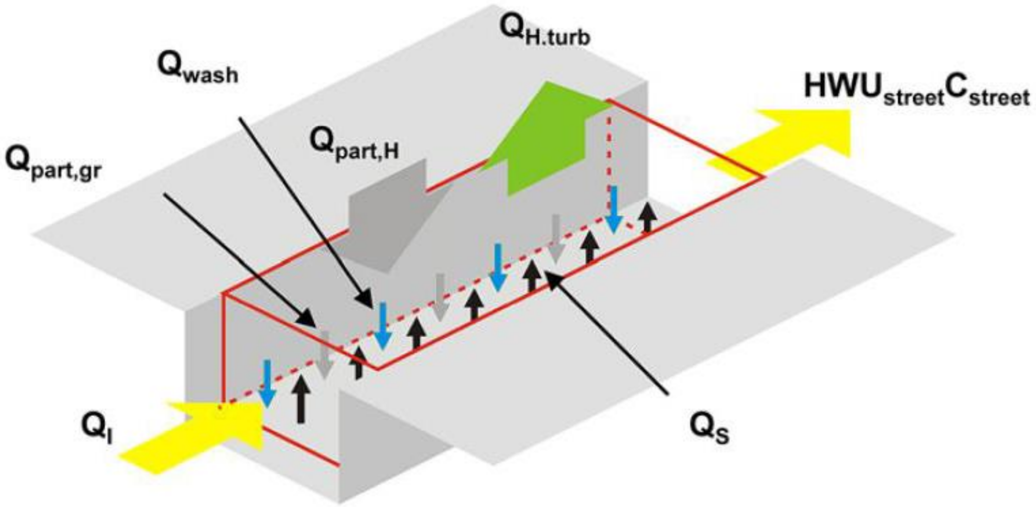




- ➢ Recirculation connected to Aspect Ratio
- ➢ Explicit modelling of the recirculation
- ➢ Direct contribution, Recirculation, Background
- ➢ C_{upwind} = Direct contr. + Recirculation
- ➢ Narrow street canyons
  $C_{downwind}$ = Direct contr. + Recirculation
- ➢ Wide street canyons
  $C_{downwind}$ = Direct contribution

3. Background: Modelling of recirculation

- SIRANE (Soulhac et al., 2011)

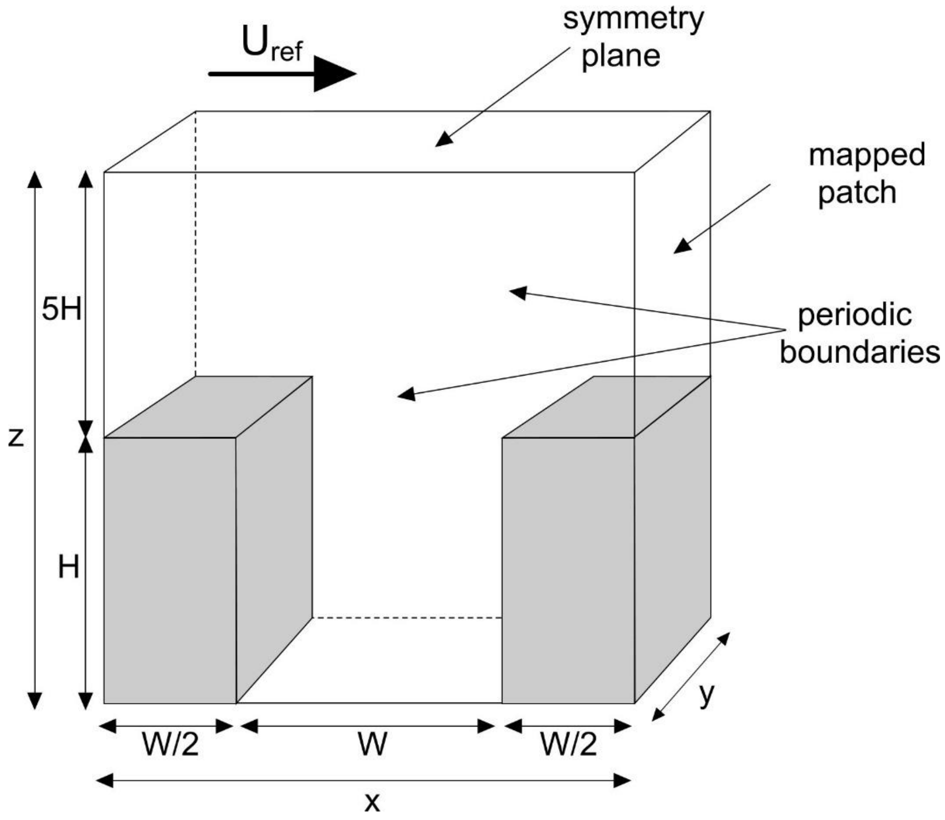


➢ Recirculation is defined by a threshold value
➢ For H/W ≥ 1/3: street canyon
➢ For H/W < 1/3: open terrain
➢ Uniform concentrations in each street segment

- Very fast and reasonable approach
- Practically cancels the hotspot variability

4. Methodology: Large Eddy Simulations

- Large Eddy Simulations in OpenFOAM v2.3.1



- ➢ Transient solution of NS equations
- ➢ Fine mesh: 100 cells per 10 m
- ➢ Standard Smagorinsky subgrid model
- ➢ PISO + convection – diffusion equation
- ➢ RAAD High Performance Computing Texas A&M University at Qatar

OpenFOAM

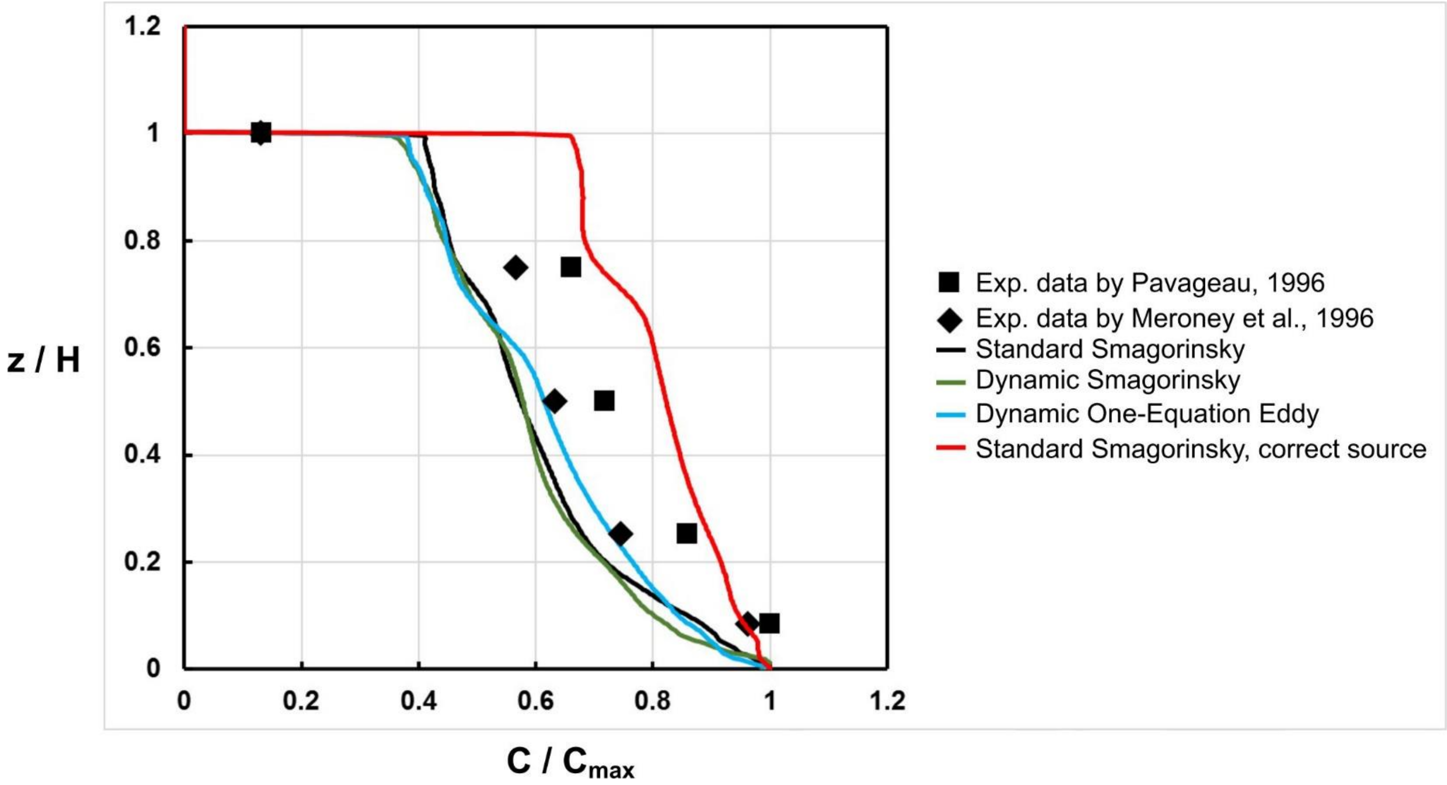
The Open Source CFD Toolbox

4. Methodology: Model verification

- Testing of SGS models
  - ➢Standard Smagorinsky
  - ➢Dynamic Smagorinsky
  - ➢One-Equation Eddy
  - ➢Dynamic One-Equation Eddy

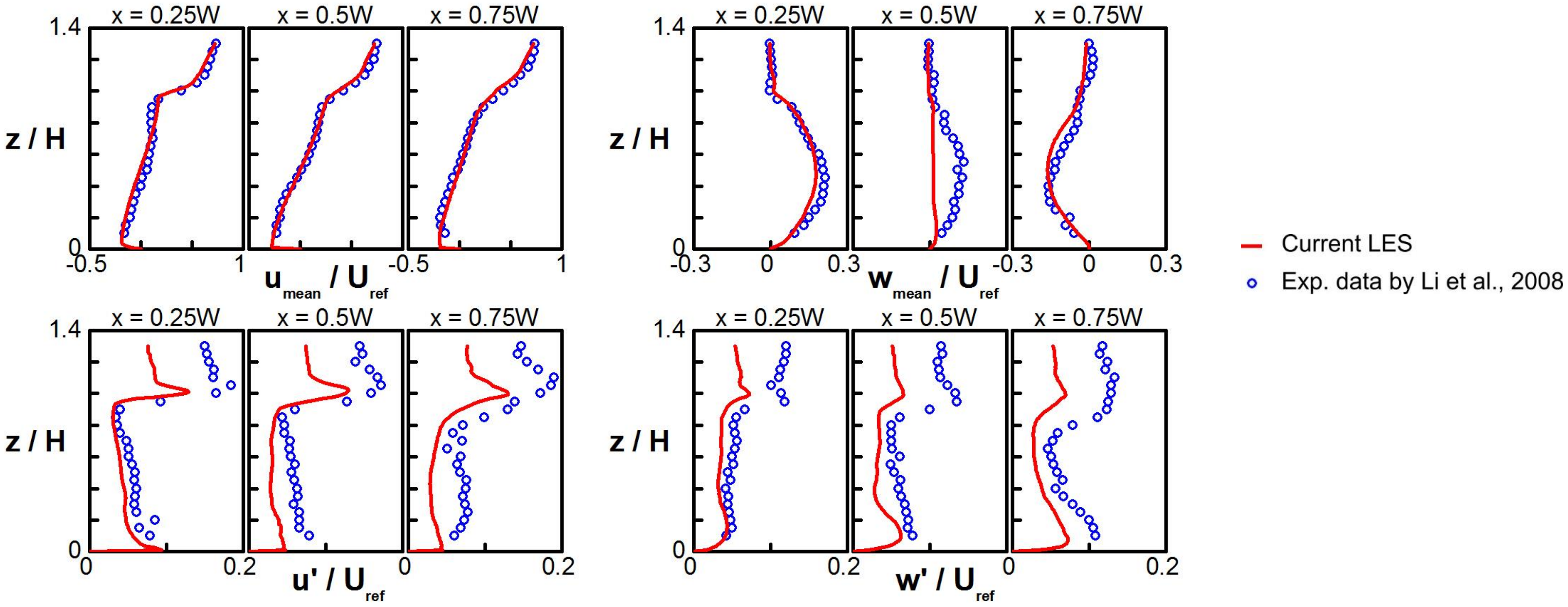
- Testing of solvers
  - ➢PISO vs PIMPLE

- Testing of boundary conditions
  - ➢Mapped vs Cyclic

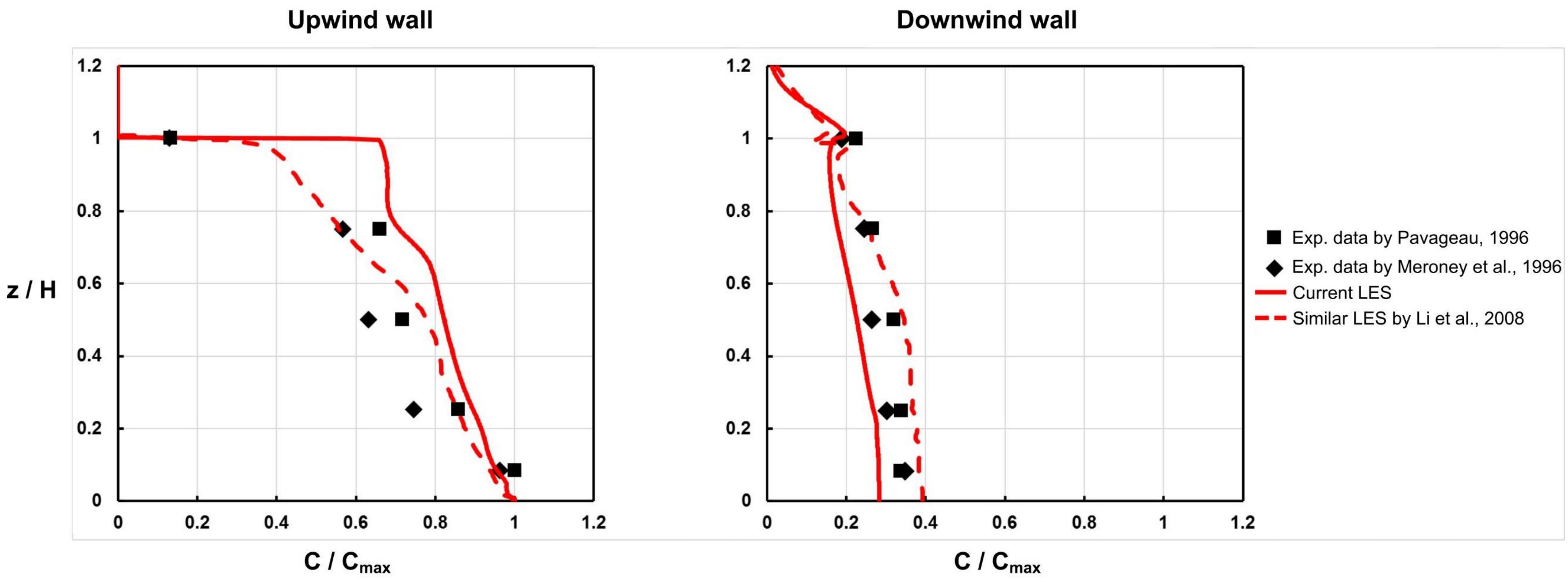


4. Methodology: Wind flow validation

- Validation results from Chatzimichailidis et al., 2016, HARMO 17

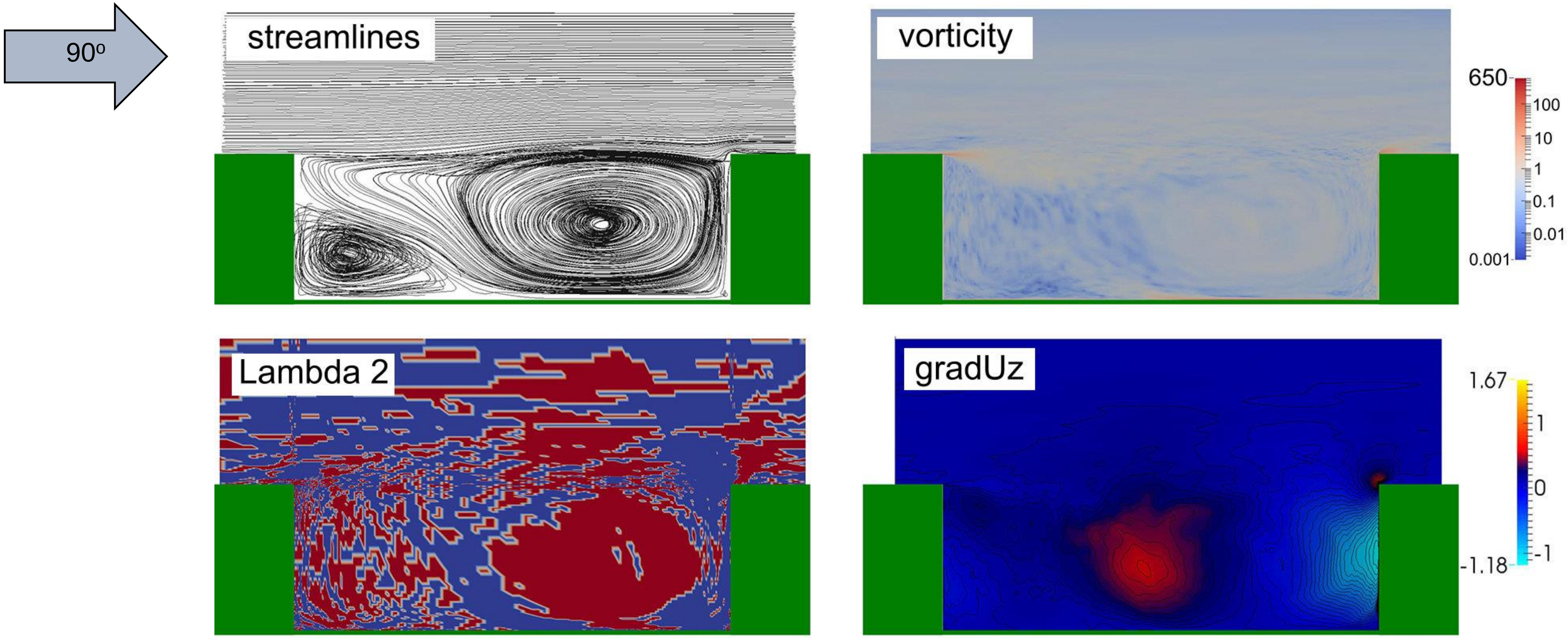


4. Methodology: Dispersion validation



5. Results: Vortex detection criteria

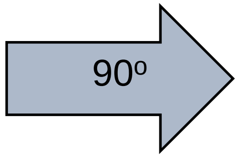
- Previous attempts using vortex visualisation methods (AR = 1/3)



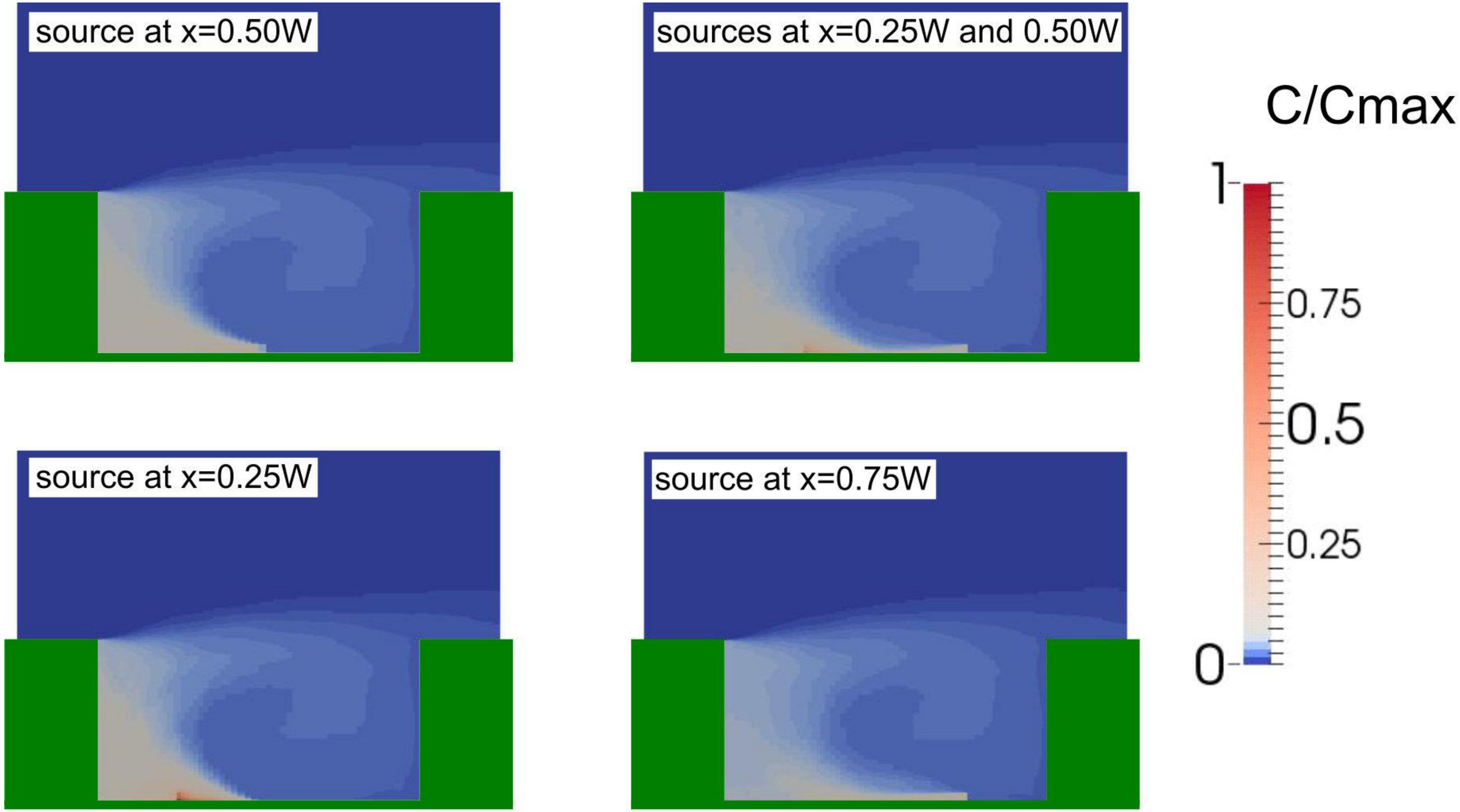
- Provided information on the vortices in the street canyon

5. Results: Aspect Ratio = 1/2

- Average normalised concentration results (750 sec)

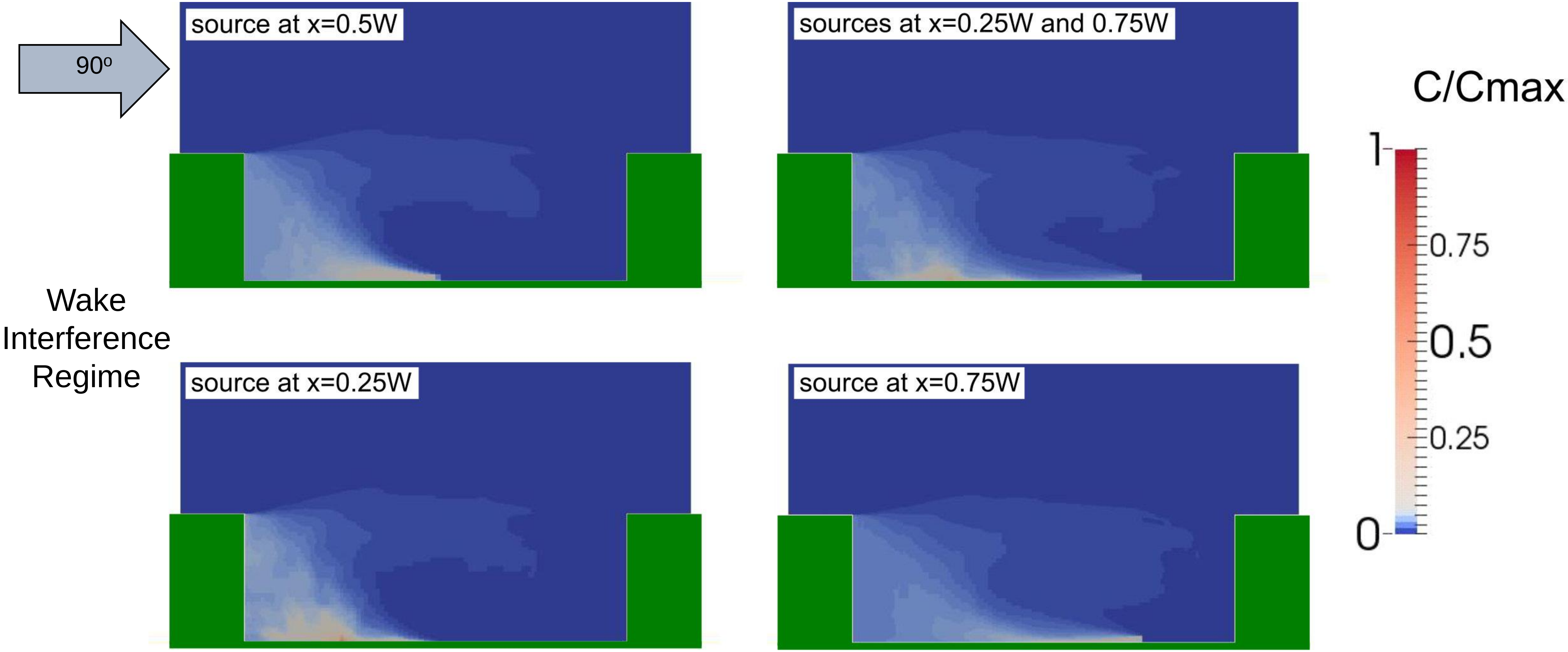


Skimming Flow Regime



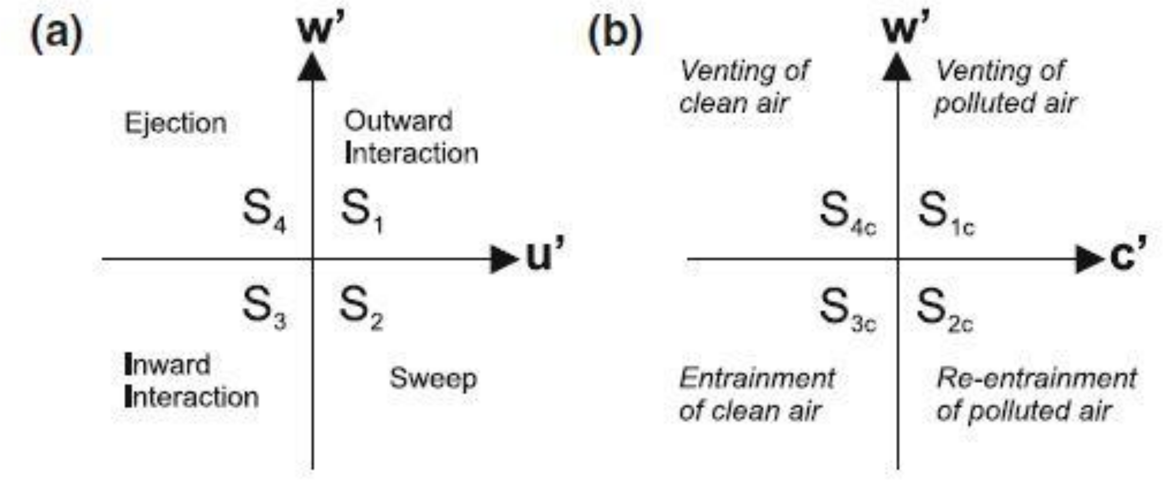
5. Results: Aspect Ratio = 1/3

- Average normalised concentration results (500 sec)



5. Results: Quadrant analysis

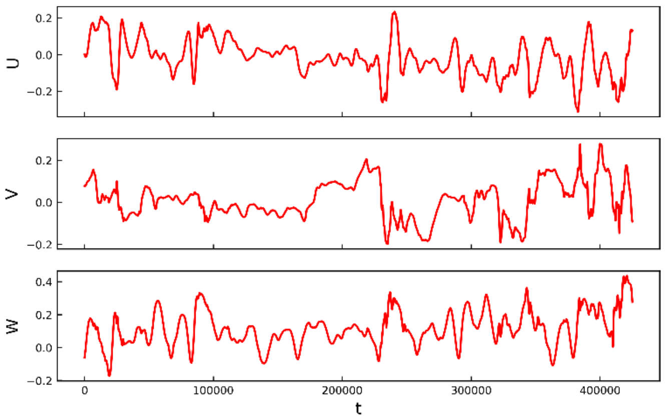
- Analysis of momentum and mass transport (Wallace et al., 1972)
- Motions as defined by Kellnerová et al., 2012 and by Nosek et al., 2017



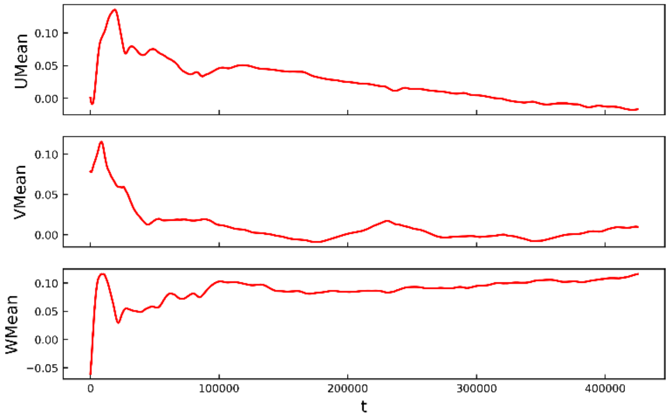
Venting of polluted air Entrainment of clean air	Cleaning Effect

5. Results: Quadrant analysis

C instantaneous

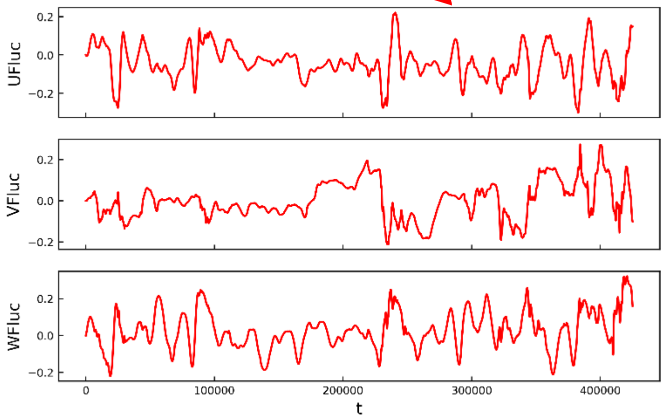


C average



Quadrant analysis for the timeseries of a single point

C fluctuation



Python script

```
if float(i)>0 and float(j)>0:
    outward+=1;
    file3.write('O');
elif float(i)<0 and float(j)>0:
    eject+=1;
    file3.write('E');
elif float(i)>0 and float(j)<0:
    sweep+=1;
    file3.write('S');
else:
    inward+=1;
    file3.write('I');
total = sweep + eject + inward + outward;
sweepPerCent = (sweep / total) * 100;
ejectPerCent = (eject / total) * 100;
inwardPerCent = (inward / total) * 100;
outwardPerCent = (outward / total) * 100;
```

Result

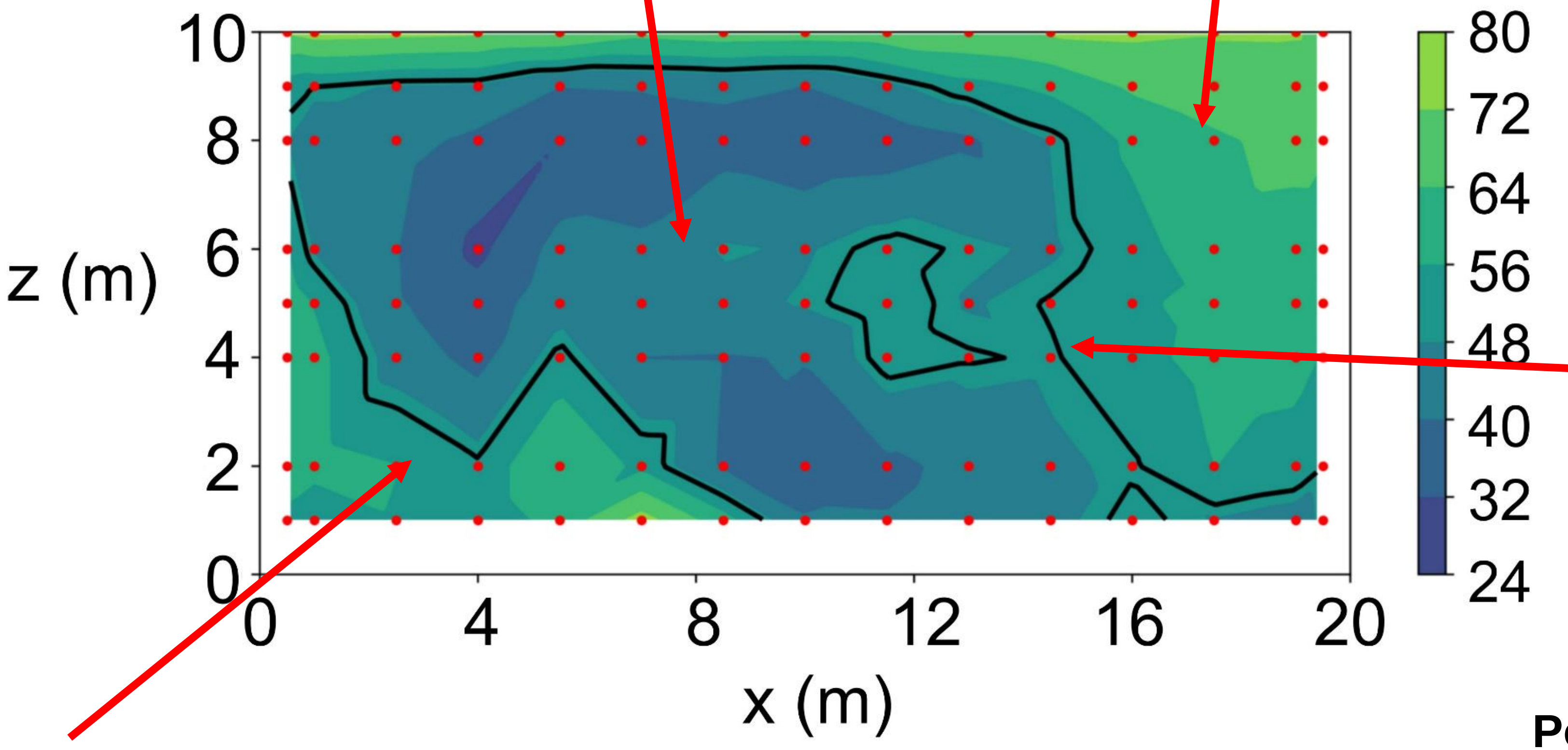
```
outward =77045, 18.13%
eject =174974, 41.17%
sweep =41925, 9.86
inward =131056, 30.84%
total =425000, 100.0%
```

5. Results: Cleaning Effect, AR = 1/2

90^o

Lower pollutant removal rate

Clean Air Entrainment



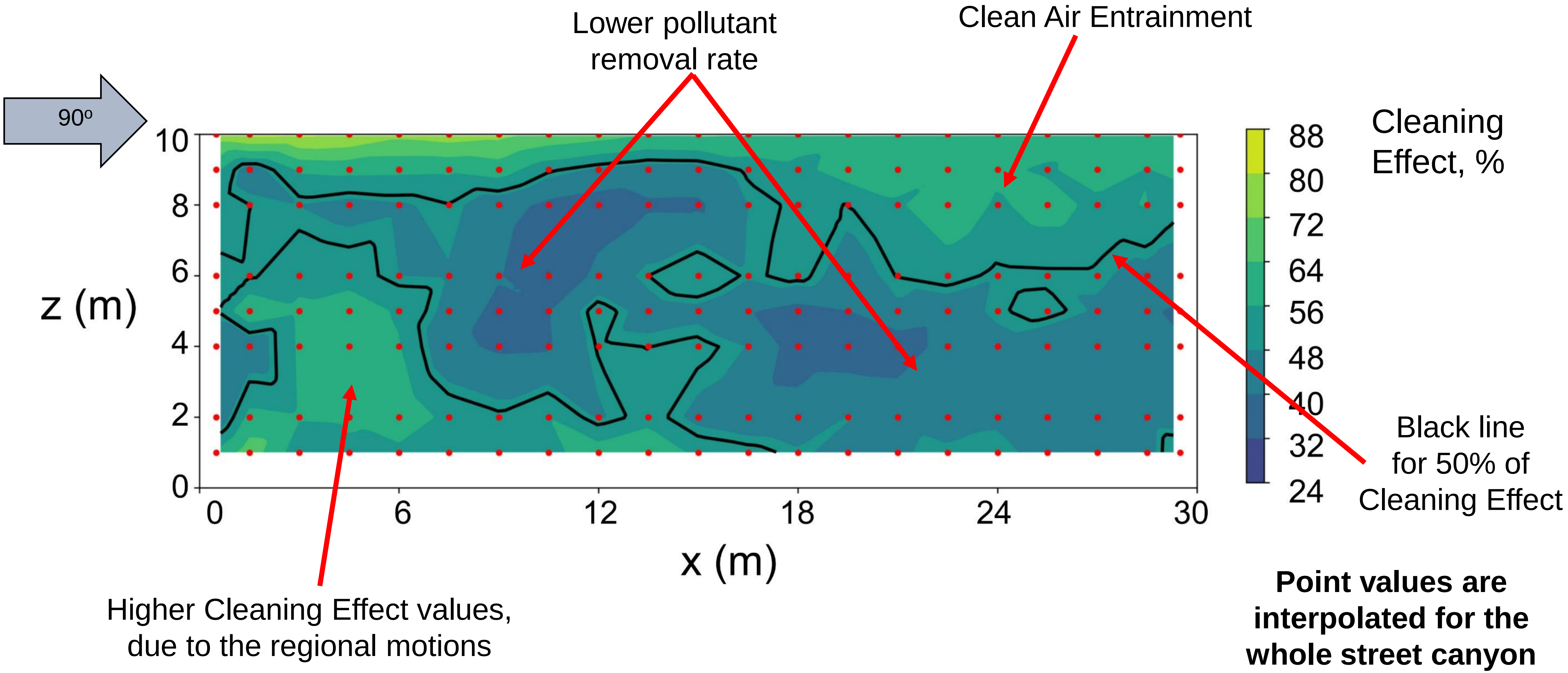
Cleaning Effect, %

Black line for 50% of Cleaning Effect

Higher Cleaning Effect values, due to the regional motions

Point values are interpolated for the whole street canyon

5. Results: Cleaning Effect, AR = 1/3



Point values are interpolated for the whole street canyon

6. Discussion

- Final goal ➔ a definition of the Recirculation Zone

- Use of Cleaning Effect
  - ➢Preliminary interpretation
  - ➢The created areas reflect the dispersion patterns
  - ➢Behavior for wide street canyons and 3D geometries

- Connections with the recirculation zone?
  - ➢How to transfer it to the model?
  - ➢Relation with the recirculation zone of current models?
  - ➢Not enough data to determine the relation between this and the recirculation zone in models

7. Future work

- Wider quasi-3D street canyons, 1/4, 1/5, 1/6
- Fully-3D urban geometries
- Effect of wind speed (Reynolds changes)
- Step-up and step-down street canyons
- Wind direction
- Solar radiation (thermal effects)

References

- Berkowicz, R., Hertel, O., Larsen, S.E., Sorensen, N.N., Nielsen, M., 1997. Modelling Traffic Pollution in Streets. National Environmental Research Institute, Roskilde, Denmark.
- Chatzimichailidis, A.E., Assael, M.J., Ketzel, M., Kakosimos, K.E., 2016. Modelling the recirculation zone in street canyons with different aspect ratios, using CFD simulation, 17th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes (HARMO 17), Budabest.
- Johnson, W.B., Ludwig, F.L., Dabberdt, W.F., Allen, R.J., 1973. An Urban Diffusion Simulation Model For Carbon Monoxide. Journal of the Air Pollution Control Association 23, 490-498.
- Kellnerová, R., Kukačka, L., Jurčáková, K., Uruba, V., Jaňour, Z., 2012. PIV measurement of turbulent flow within a street canyon: Detection of coherent motion. Journal of Wind Engineering and Industrial Aerodynamics 104–106, 302-313.
- Li, X.-X., Leung, D.Y.C., Liu, C.-H., Lam, K.M., 2008a. Physical Modeling of Flow Field inside Urban Street Canyons. Journal of Applied Meteorology and Climatology 47, 2058-2067.
- Li, X.-X., Liu, C.-H., Leung, D.C., 2008b. Large-Eddy Simulation of Flow and Pollutant Dispersion in High-Aspect-Ratio Urban Street Canyons with Wall Model. Boundary-Layer Meteorol 129, 249-268.
- Meroney, R.N., Pavageau, M., Rafailidis, S., Schatzmann, M., 1996. Study of line source characteristics for 2-D physical modelling of pollutant dispersion in street canyons. Journal of Wind Engineering and Industrial Aerodynamics 62, 37-56.
- Nosek, Š., Kukačka, L., Jurčáková, K., Kellnerová, R., Jaňour, Z., 2017. Impact of roof height non-uniformity on pollutant transport between a street canyon and intersections. Environmental Pollution 227, 125-138.
- Ottosen, T.-B., Ketzel, M., Skov, H., Hertel, O., Brandt, J., Kakosimos, K.E., 2016. A parameter estimation and identifiability analysis methodology applied to a street canyon air pollution model. Environmental Modelling & Software 84, 165-176.
- Pavageau, M., 1996. Concentration fluctuations in urban street canyons–groundwork for future studies. Meteorological Institute of the University of Hamburg Tech. Rep.
- Soulhac, L., Salizzoni, P., Cierco, F.X., Perkins, R., 2011. The model SIRANE for atmospheric urban pollutant dispersion; part I, presentation of the model. Atmospheric Environment 45, 7379-7395.
- Wallace, J.M., Eckelmann, H., Brodkey, R.S., 1972. The wall region in turbulent shear flow. Journal of Fluid Mechanics 54, 39-48.
- Yamartino, R.J., Wiegand, G., 1986. Development and evaluation of simple models for the flow, turbulence and pollutant concentration fields within an urban street canyon. Atmospheric Environment (1967) 20, 2137-2156.

Ευχαριστώ!

Thank you!

This publication was made possible by a NPRP award [NPRP 7-674-2-252] from the Qatar National Research Fund (a member of The Qatar Foundation).

The statements made herein are solely the responsibility of the authors.

الصندوق القطري لرعاية البحث العلمي
Qatar National Research Fund
Member of Qatar Foundation

TEXAS A&M
UNIVERSITY at QATAR