Thermal stratification and vegetation effects on the urban micro-climate – a CFD study

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Motivation:

- Singapore - a very heterogeneous urban morphology.
- Increasing population and UHI phenomenon => land and liveability challenge.
- Need for better urban planning and designing that provides good thermal and aural comfort.

Aim:

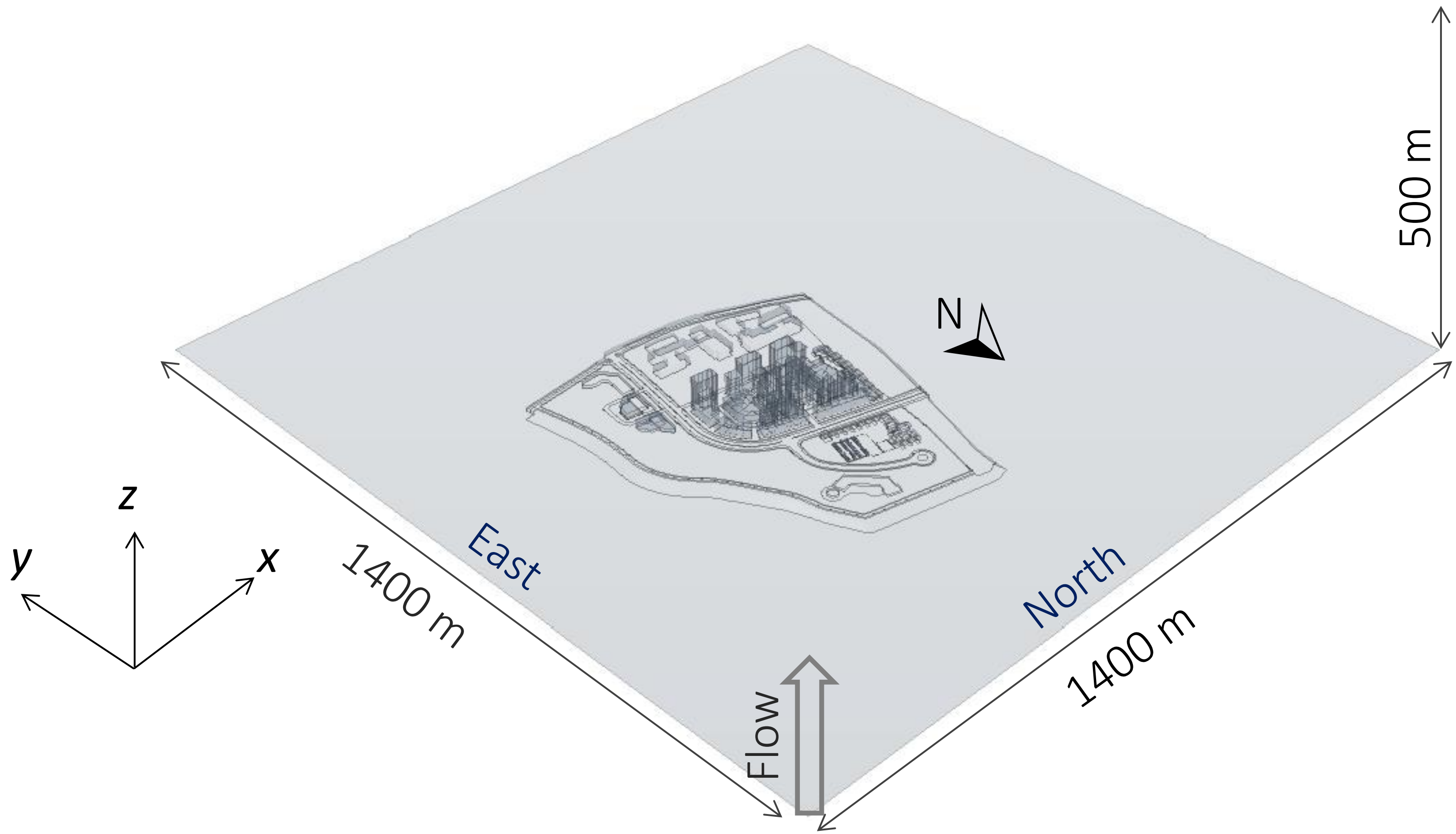
- Improve our understanding on urban-microclimate – CFD and measurements.
- Develop an Urban Microclimate-Multi physics Integrated Simulation Tool (UM-MIST) that incorporates effects of thermal stratification, vegetation, anthropogenic heat flux and waterbody.

Objective:

CFD on a residential estate in Singapore.

(i) Neutral flow
(ii) Unstable stratified flow
(iii) Unstable stratified flow and vegetation.

Computational Domain of a Residential Estate



- Terrain – approx. 5 m above ground.
- Building height - 10 m to 60 m.
- Assumption - smooth wall.
- Seletar met - u = 4 m/s @ z = 14 m
- North & East – logarithmic profile
- South & West - outflow
- Top – symmetry
- Bottom – very rough wall outside RE

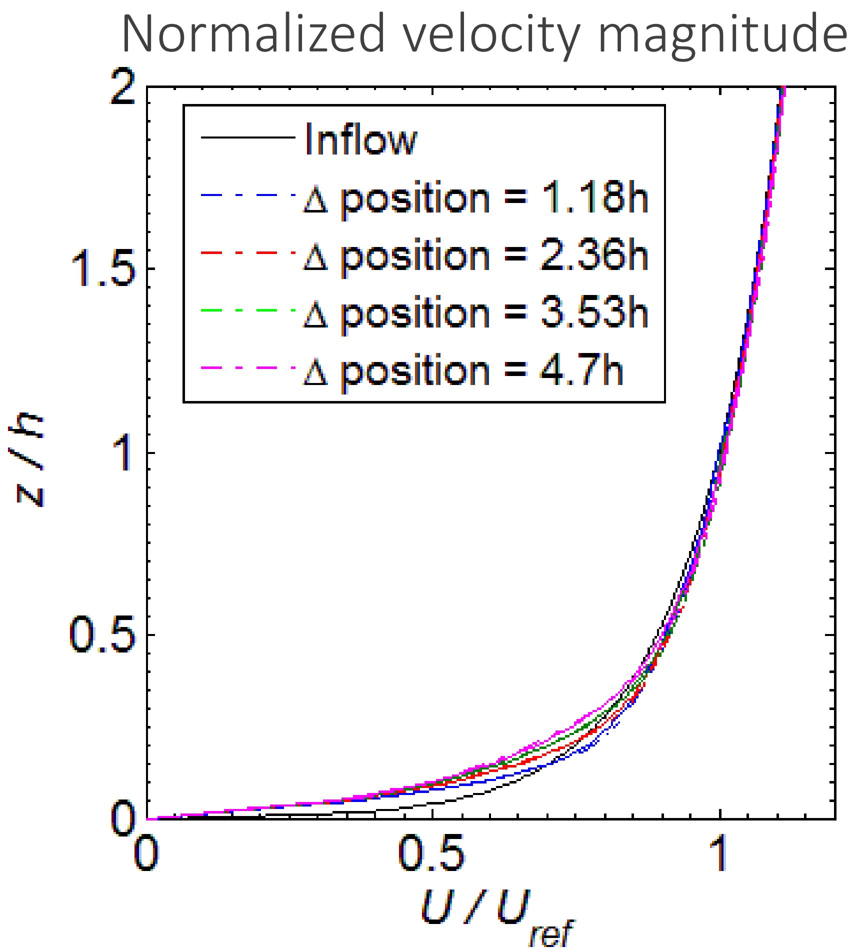
Numerical settings:

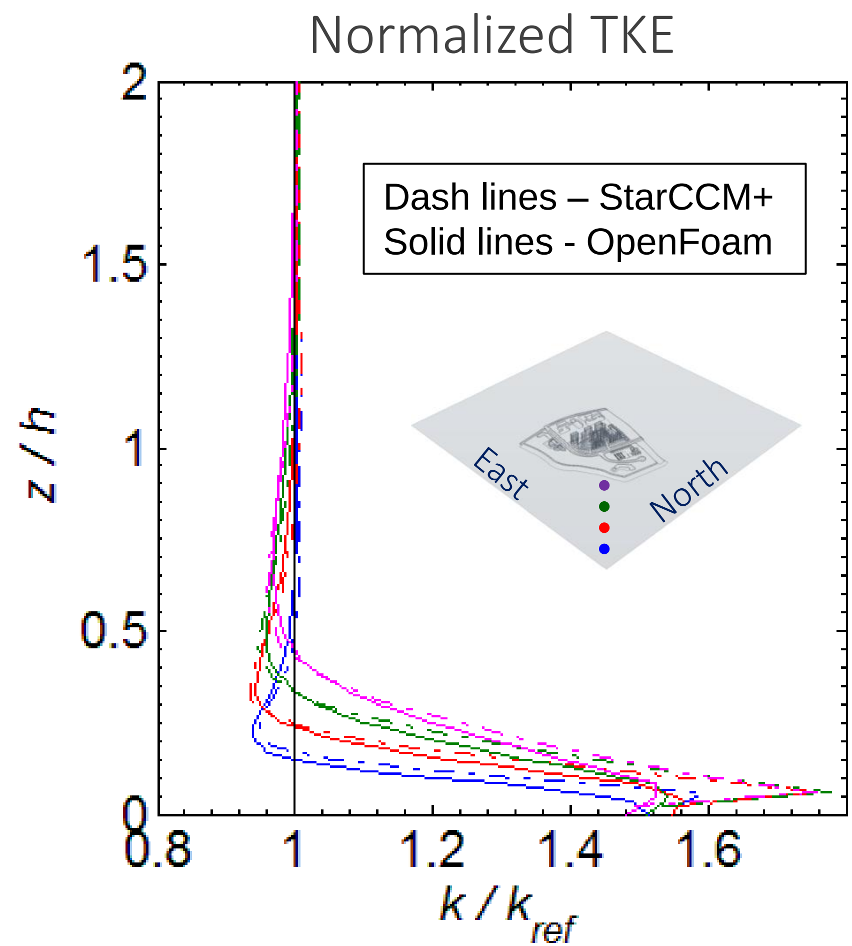
- Snappy Hex methodology.
- Six levels of mesh refinement (min. res. = 0.3125 m at the building corner and max. res. = 20 m).
- k_s and c_s are chosen such that they satisfy the near-wall mesh criteria (Blocken et al. 2007).
- Total no. of cells = 8.5 million.

- StarCCM+ v 9.06 (SC+) and OpenFOAM v 2.3 (OF) – same mesh.
- Steady RANS + k-ε turbulence closure.
- Thermal effects with Boussinesq approximation.
- Second-order schemes for Navier-Stokes.
- Turbulence - First-order in OF and Second-order in SC+.
- SIMPLE pressure-velocity coupling

Neutral flow

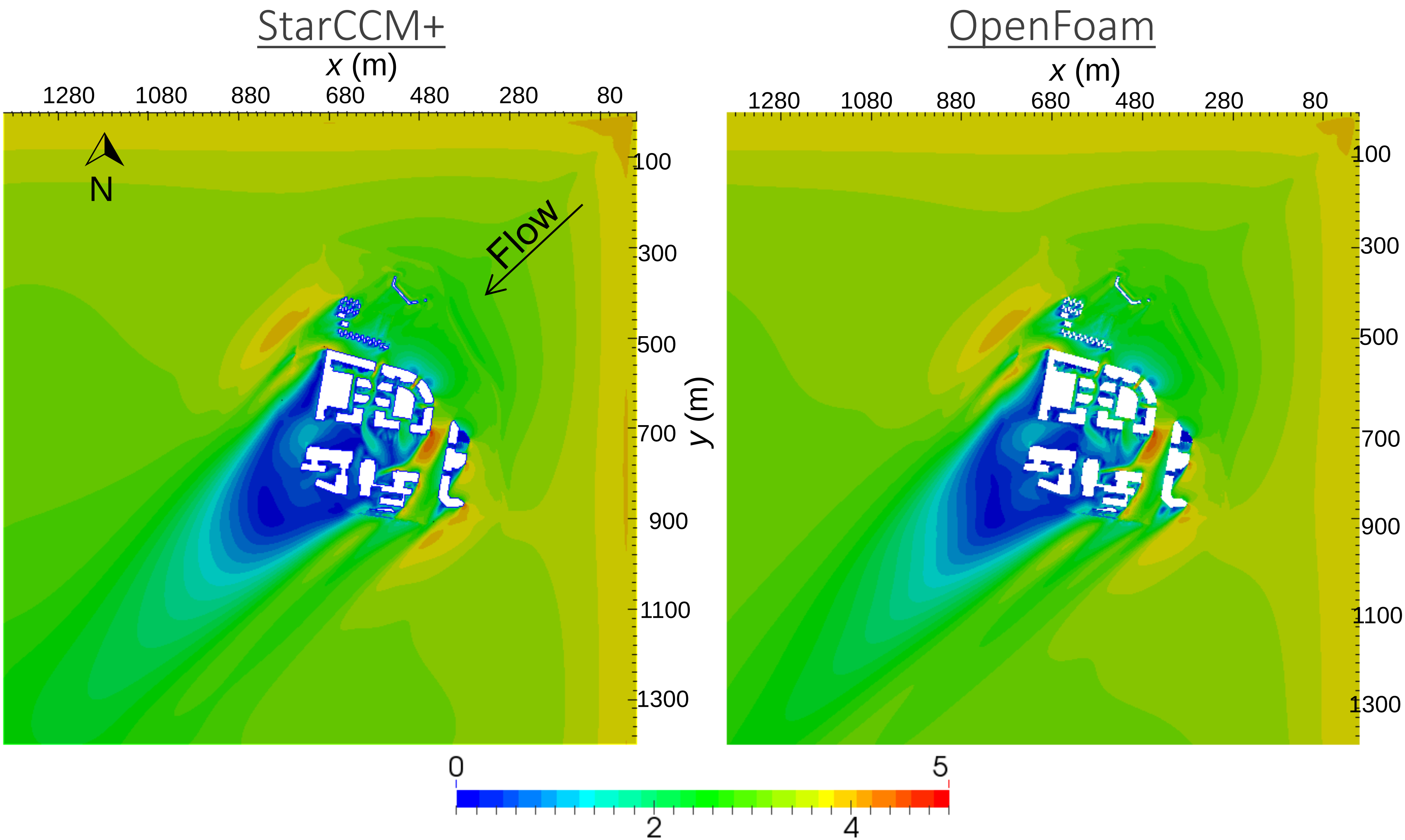
Approach flow





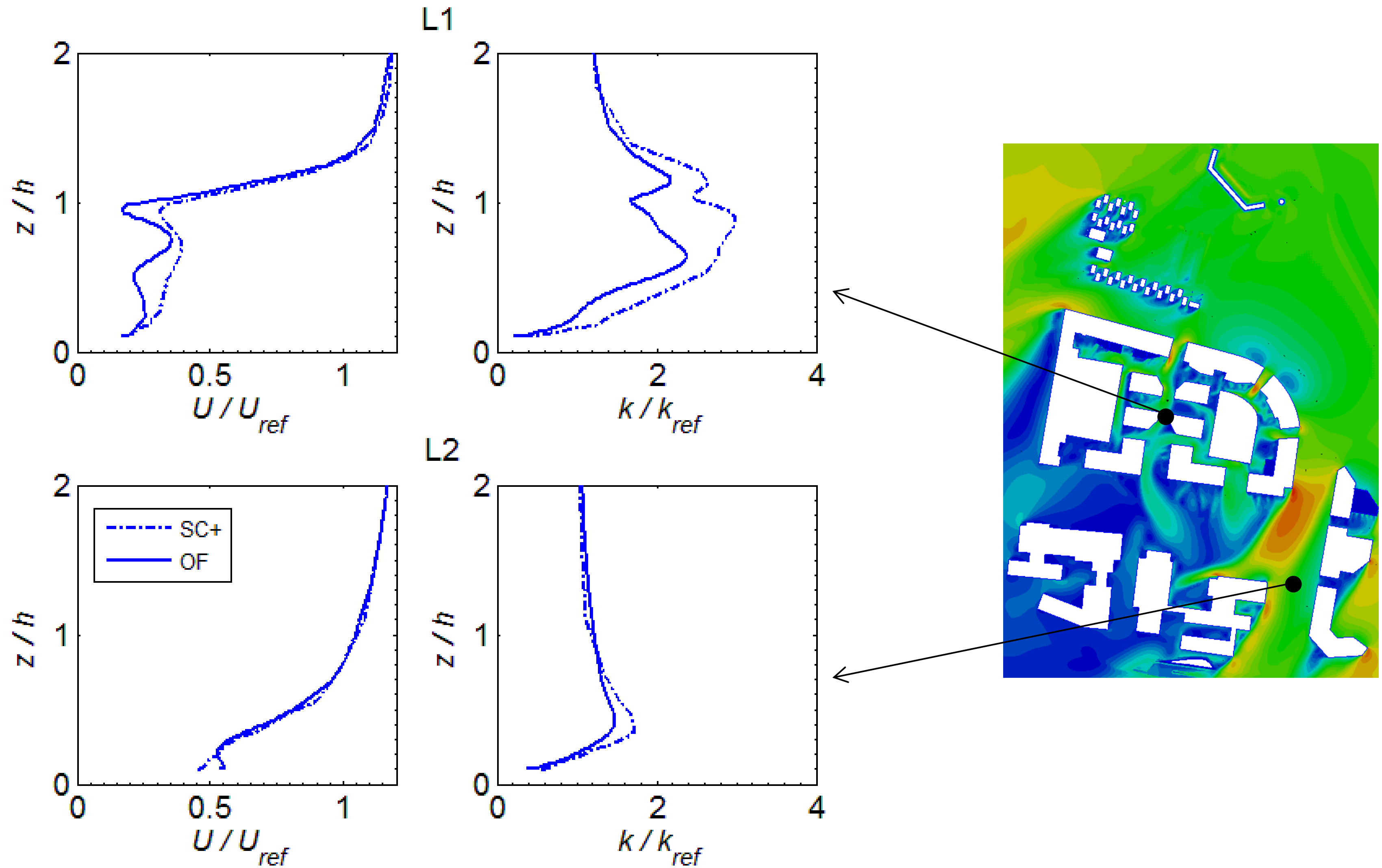
- U_{ref} and k_{ref} are at h = 60 m at inflow
- Small increase in k with increasing distance from inlet
- Larger peak in k near the ground for SC+

Contours of velocity magnitude @ z = 10 m



Good qualitative agreement

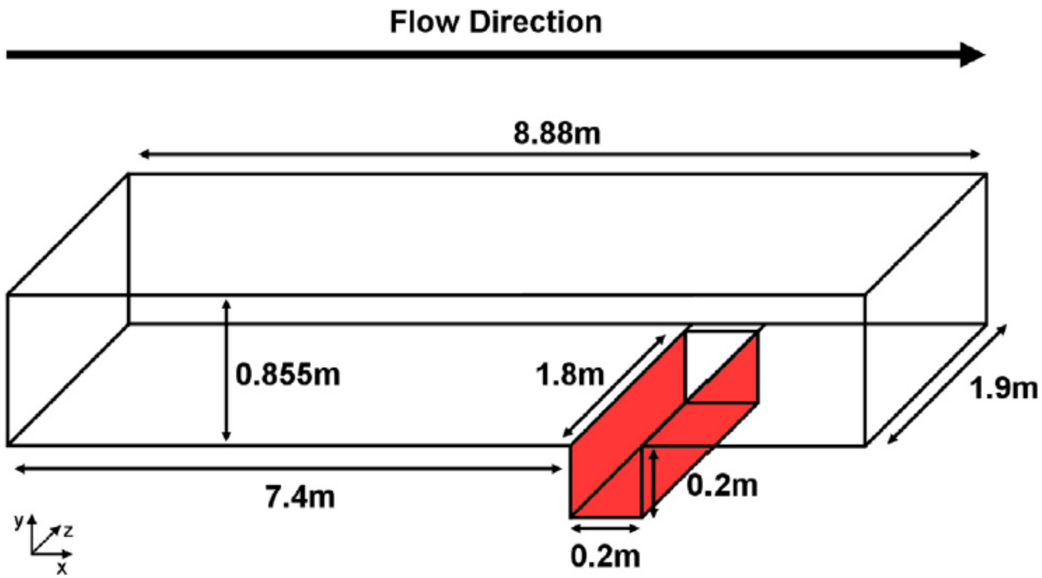
Vertical profiles from SC+ and OF:



- For $z \leq h$, SC+ shows slightly larger values of u and k than OF
- A fair quantitative agreement for neutral flow

Unstable flow

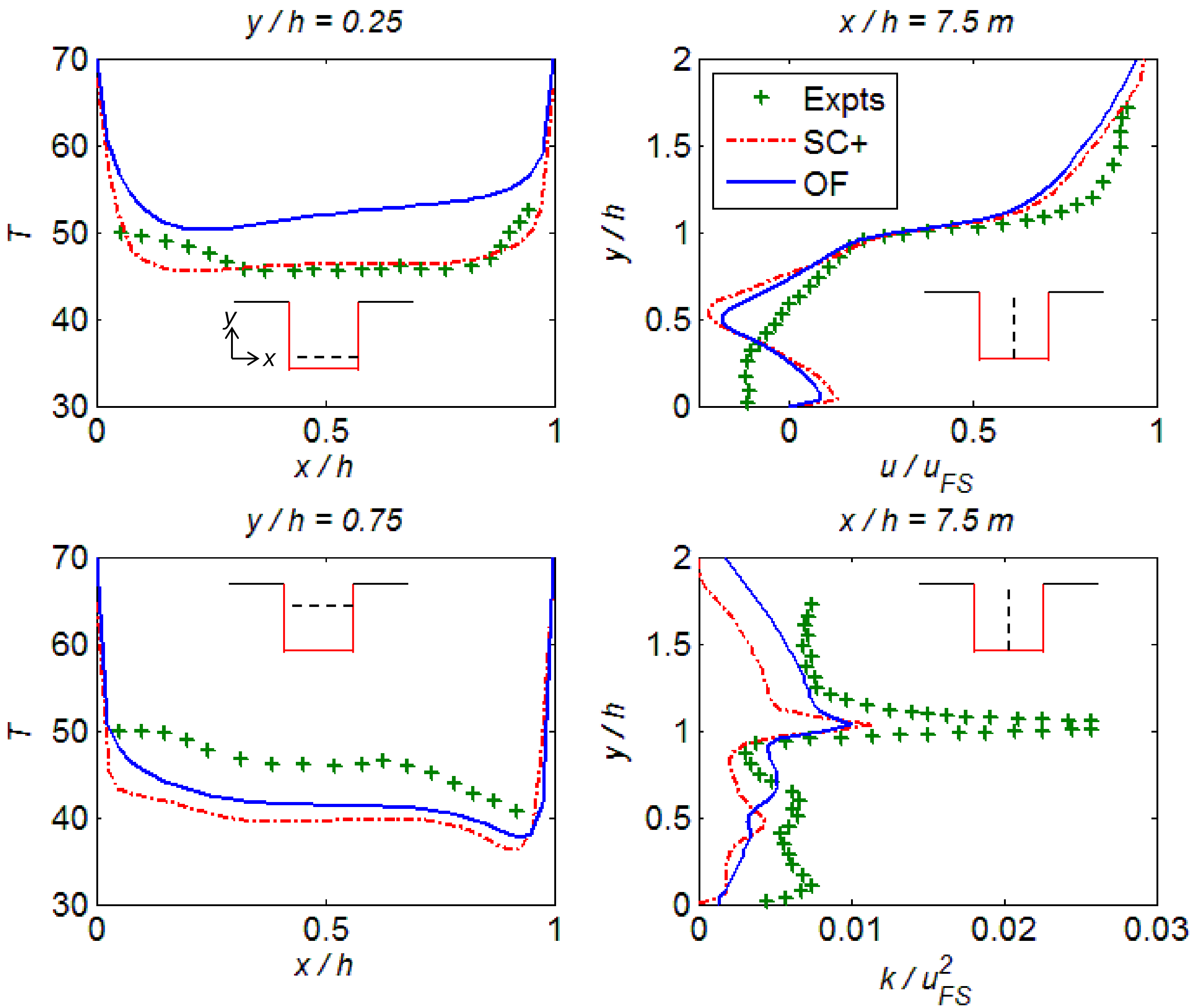
A 2-D validation study for buoyancy (Allegrini et al., 2014):



Source: Fig. 1 in Allegrini et al., 2014

- Inlet – measured values of *u* and *k*.
- Outlet – convective boundary condition
- Top – symmetry
- Bottom – smooth wall
- Canyon surfaces – uniformly heated to 70°C
- Re = 19200 and Fr = 6.75
- $0.05 < y^+ < 4.5$; 30800 cells.

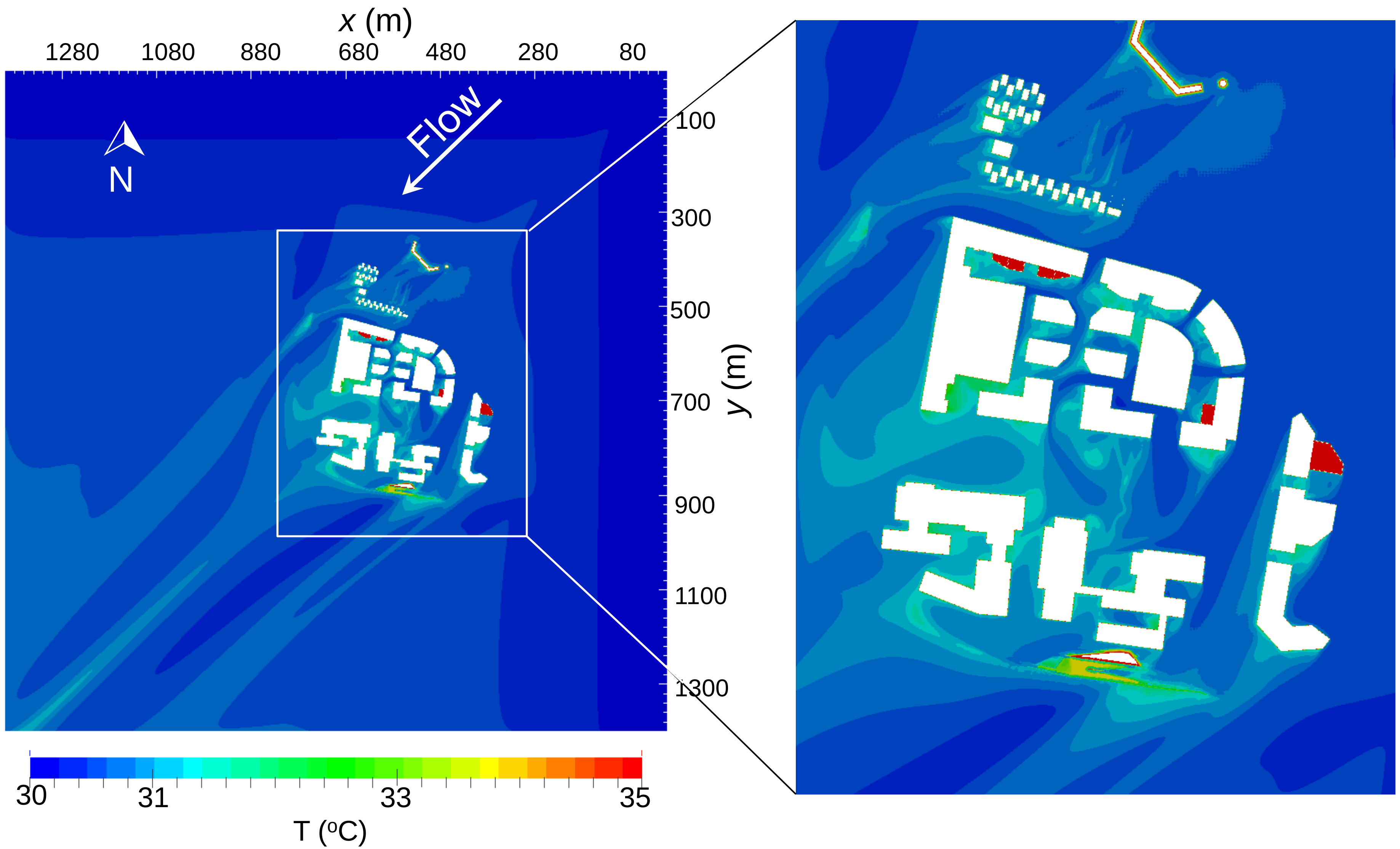
Comparison of SC+ and OF with experiments:



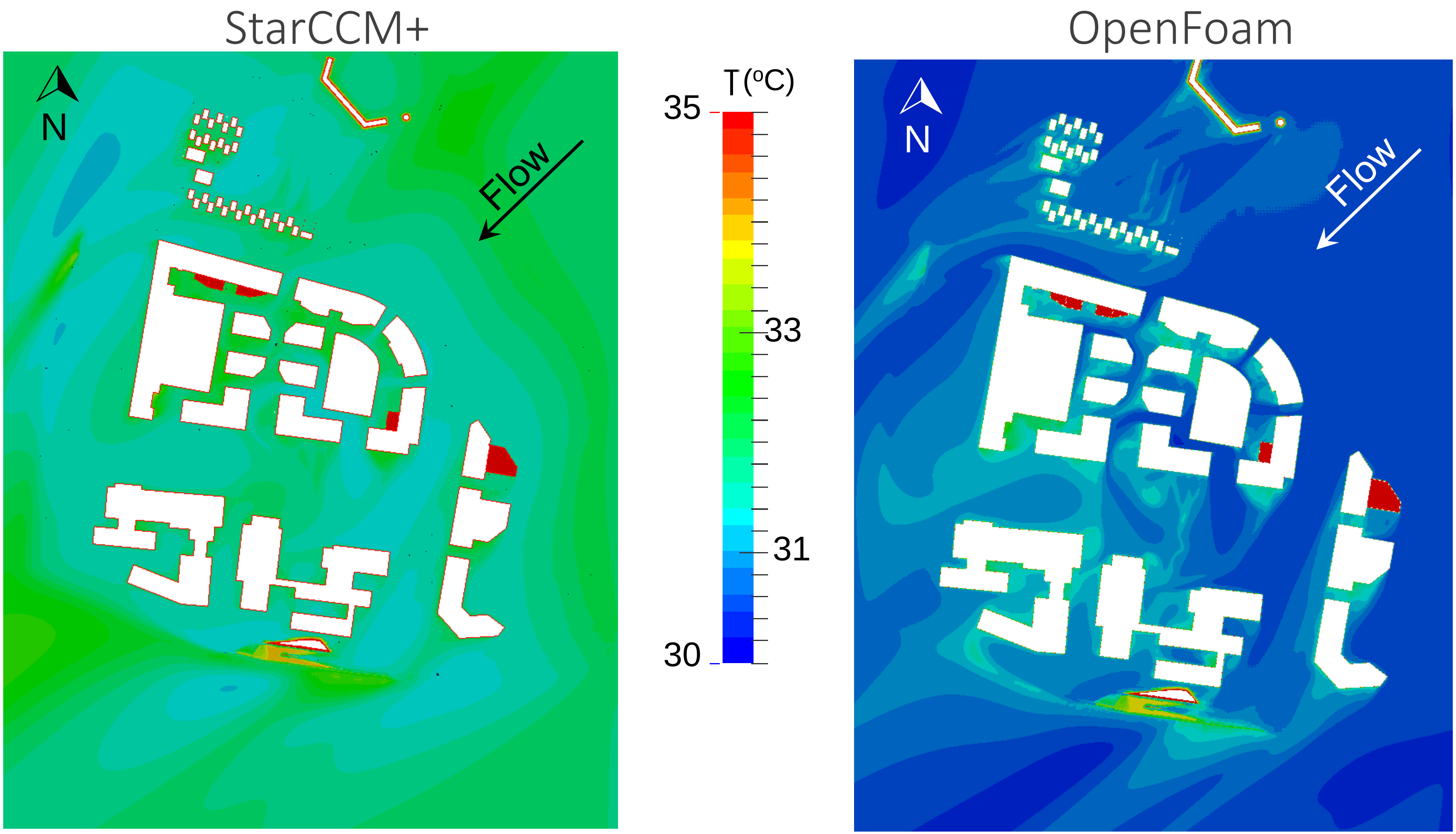
- For T, SC+ performs well close to the bottom canyon.
- Overall, a good agreement between SC+ and OF with experiments.

Temperature contour @ z = 10 m - OpenFoam

All surfaces uniformly heated to 35°C, 5°C higher than the inlet.

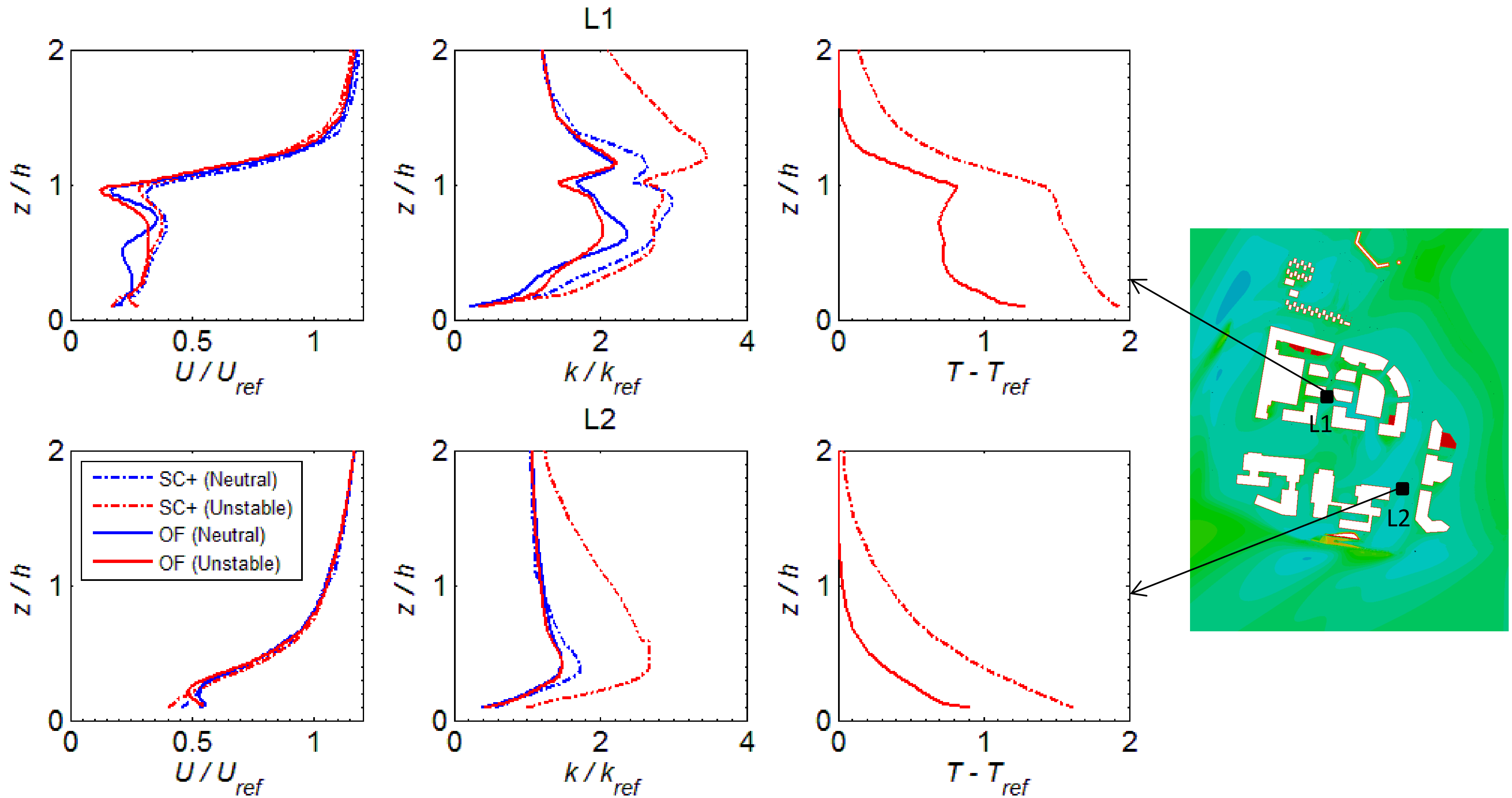


Contours of T @ z = 10m



OF shows lower values of T than SC+ - why?

Vertical profiles of neutral and unstable flow at L1 and L2 for SC+ and OF:



- Neutral and unstable profiles are almost same in OF => weak buoyancy.
- Could it be due to better wall treatments in SC+ ? – a 3D validation study
- Further slides: starccm+

CFD coupling with solar irradiance

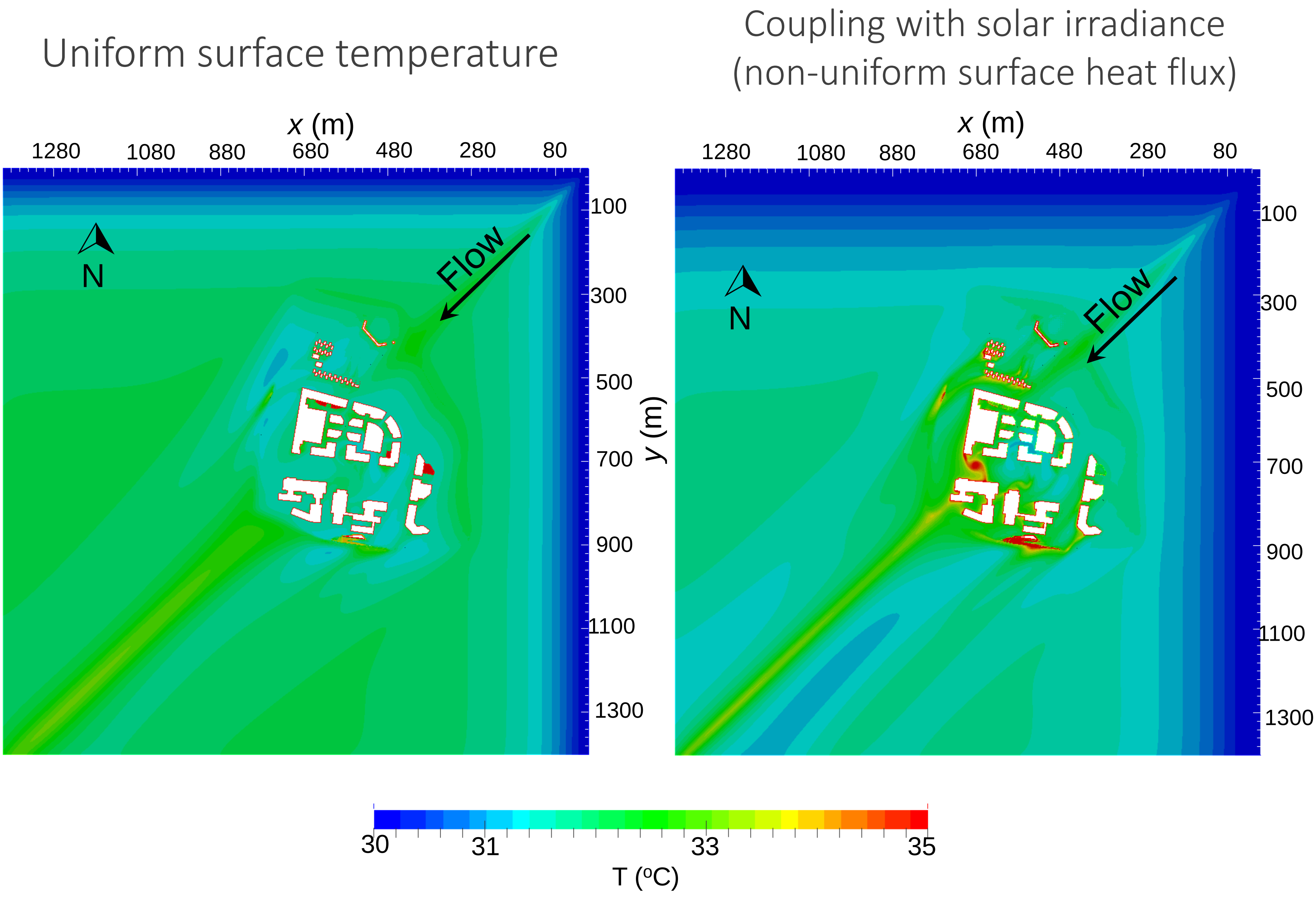
Modelling of Solar irradiance – surface heat flux input to CFD:

- Perez all-weather sky model for natural light source from the sun and the sky dome.
  - Proven to be good for Singapore
  - Input – direct normal irradiance and diffuse horizontal irradiance for a given date, time and geographical location.
  - Output – direction and radiation intensity of light sources.

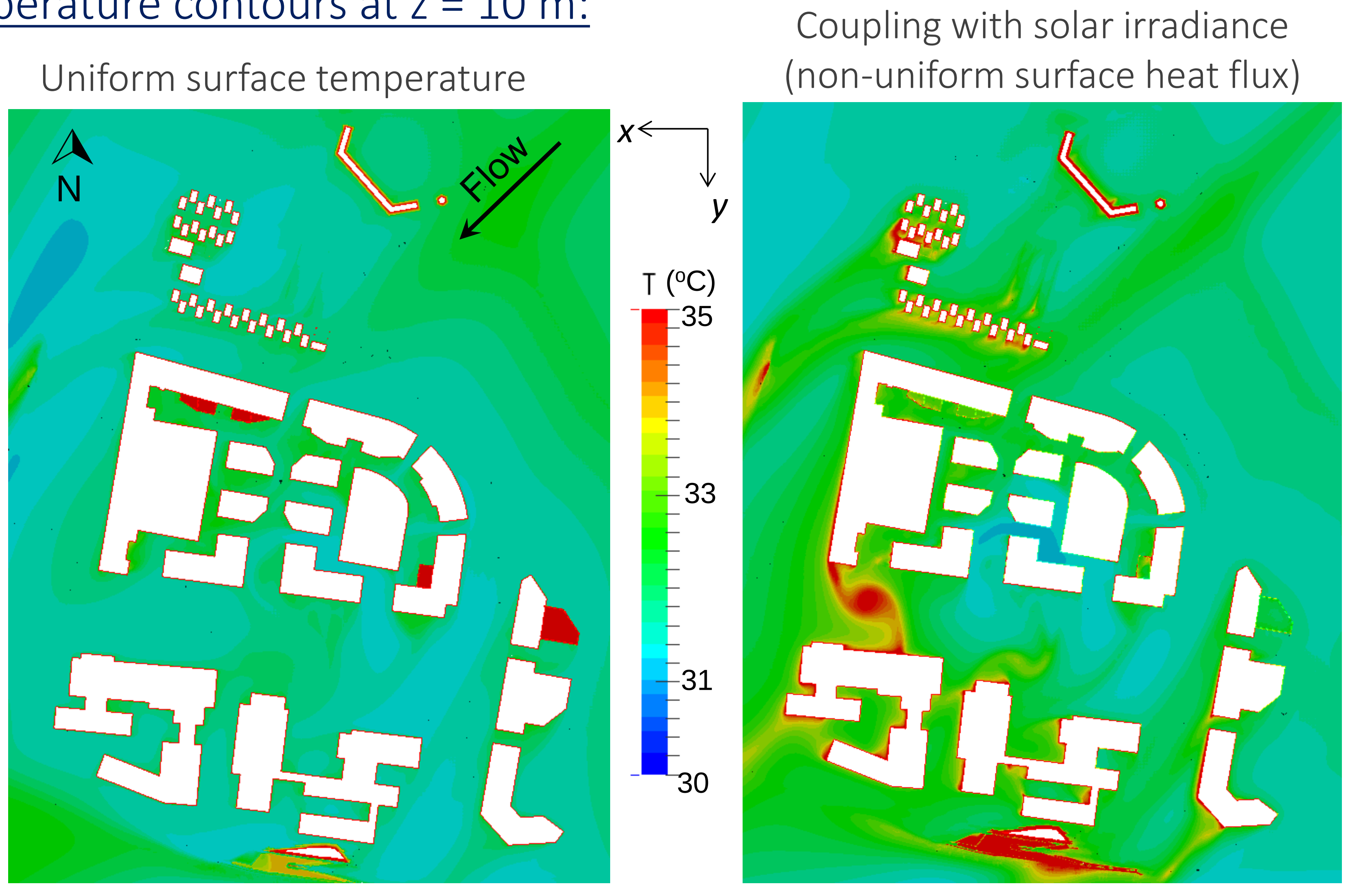
- Ray tracing solver to account for ambient bounces.
  - Lambertian model for surface diffusivity
  - Ambient bounces = 2
  - Appropriate absorption coefficient for different types of surfaces (waterbody, concrete, pavement, grass, glass, wall)

- Radiance solver; simulations at 16:30 p.m. on June 21.

Temperature contours at z = 10 m:

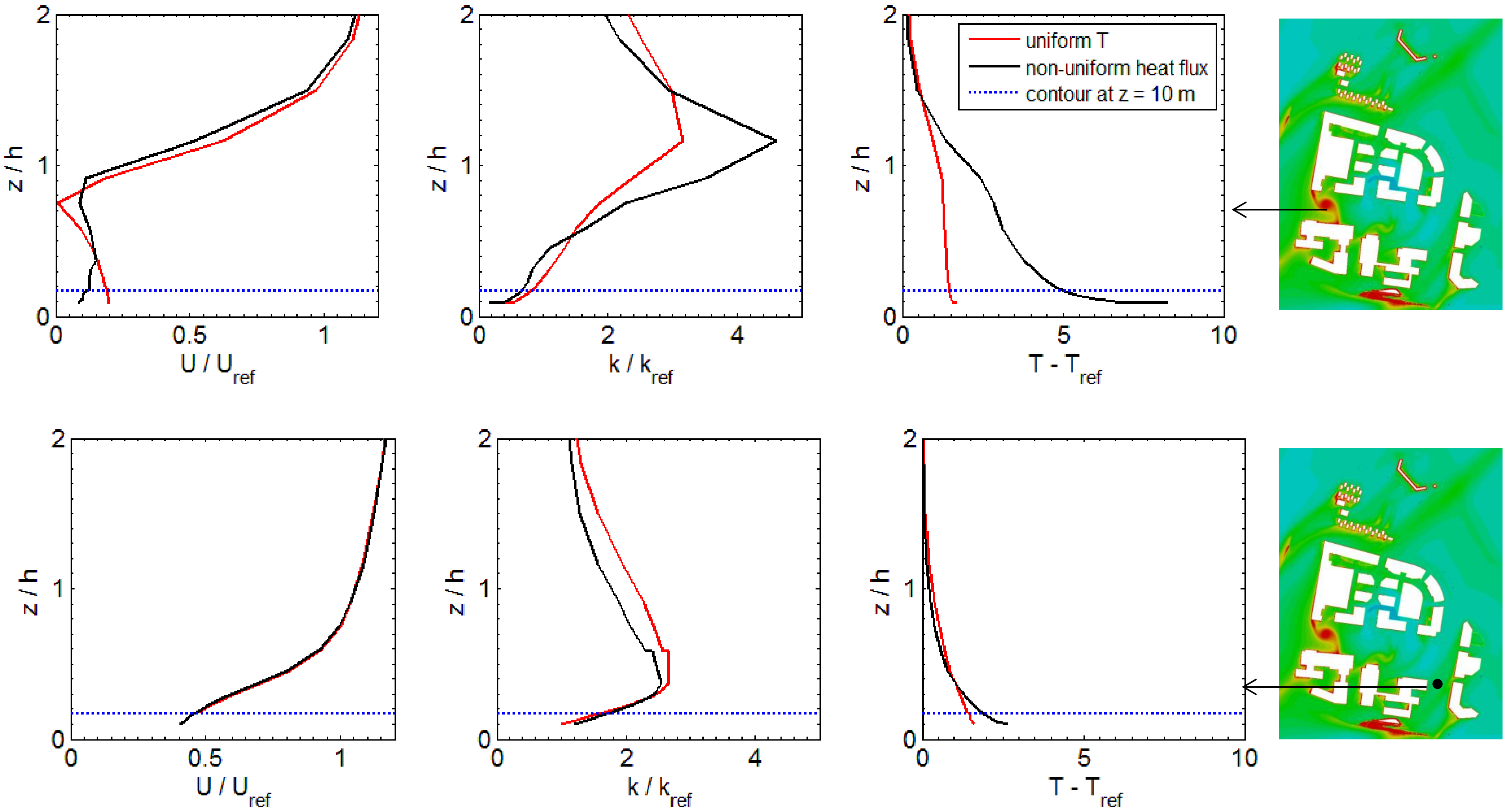


Temperature contours at z = 10 m:



A very different distribution of temperature!!!!

Vertical profiles of unstable flow:



Notable differences in the vertical profiles of k and T

Modelling vegetation

A validation study (Gromke & Blocken, 2015):

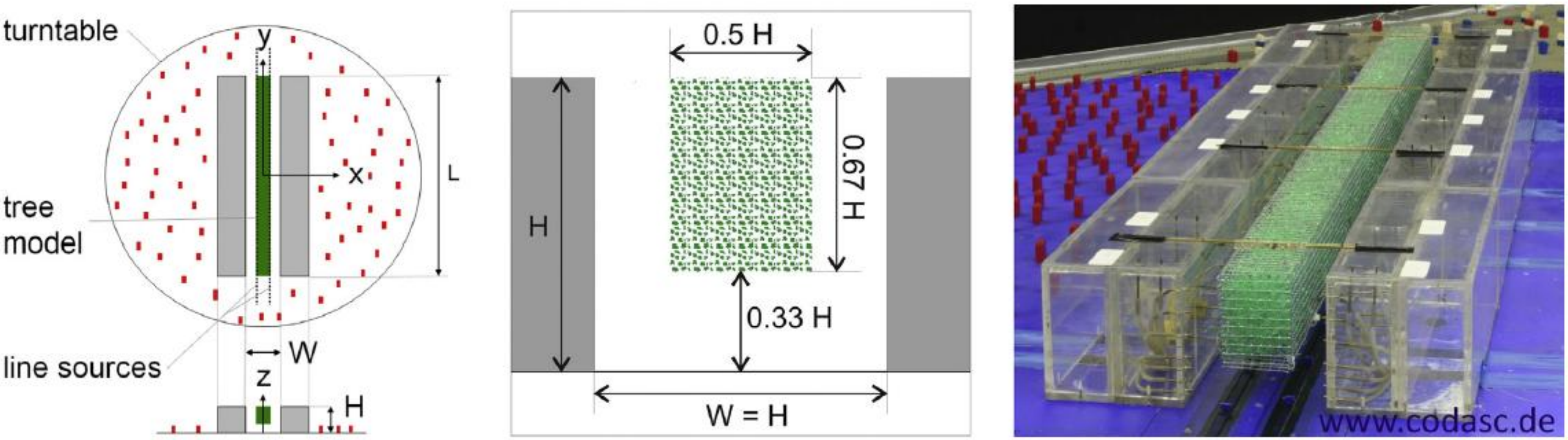
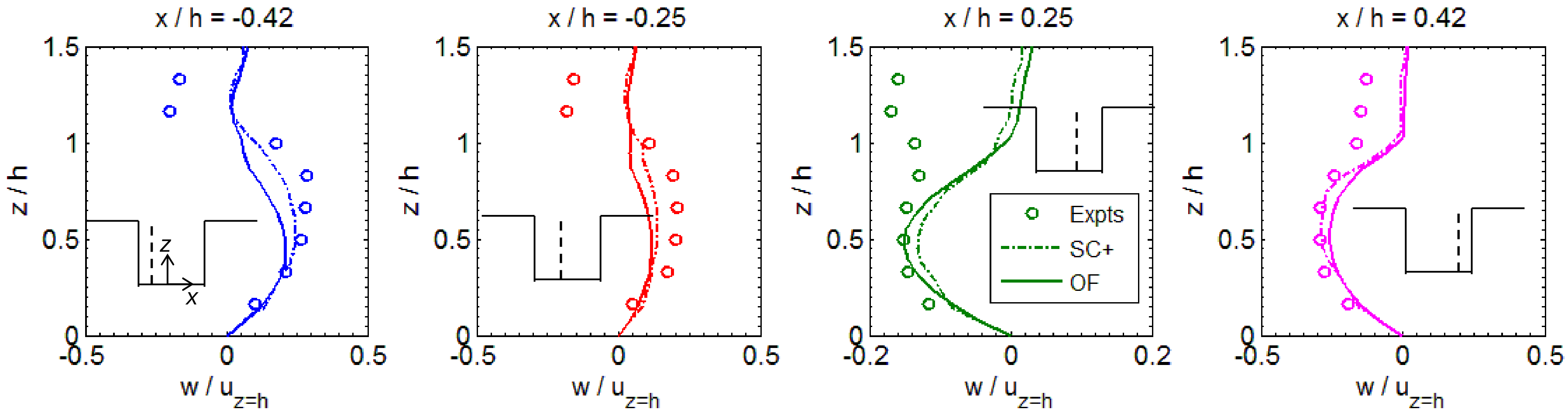


Fig. 8. Isolated urban street canyon model with avenue-tree row (CODASC, 2008).

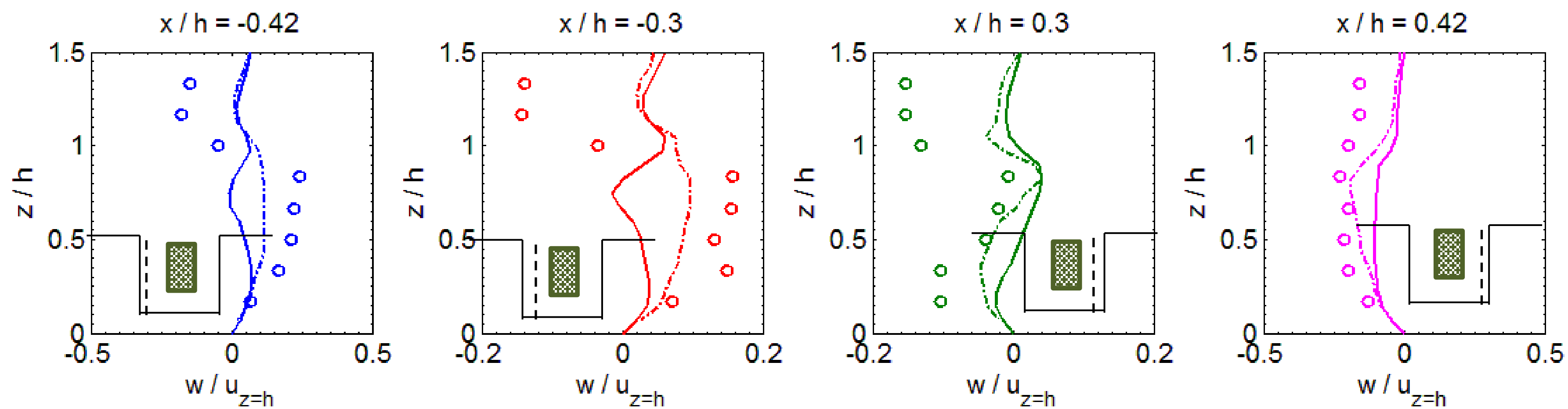
- Domain size – 40*h* x 24*h* x 8*h* & 0.8 million mesh points.
- Inlet – power law.
- Outlet – pressure outlet.
- Top & Span – symmetry
- Bottom – rough wall except the buildings and street canyon.
- Vegetation – pressure loss coeff = 250 /m; 97% pore volume fraction

Comparison of SC+ and OF with experiments:

No trees in street canyon



Trees in street canyon



Improvement in OF tree modelling is required

Vegetation in a residential site:

(Gromke et al., 2015)

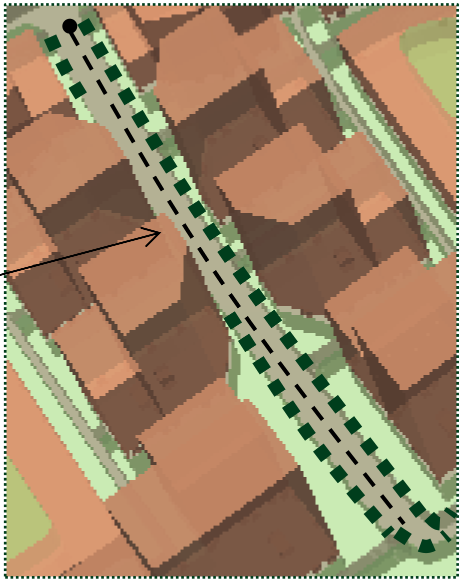
- Additional source terms in the transport equations.

- Tree specs:
  - Crown – 5 m x 5 m x 6 m
  - Trunk – 6 m tall
  - Distance = 10 m
  - LAD = 0.55 m^2/m^3
  - Cooling power = 137.5 W/m^3.

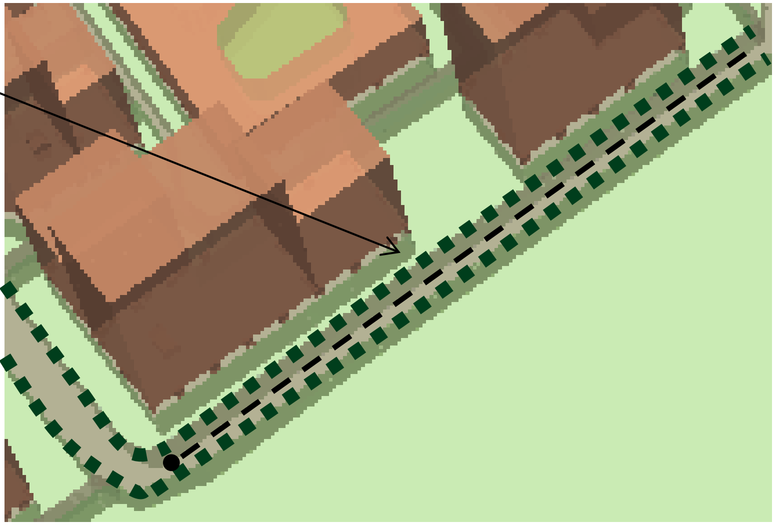
- Shading of trees is ignored.

Vegetation in a residential site:

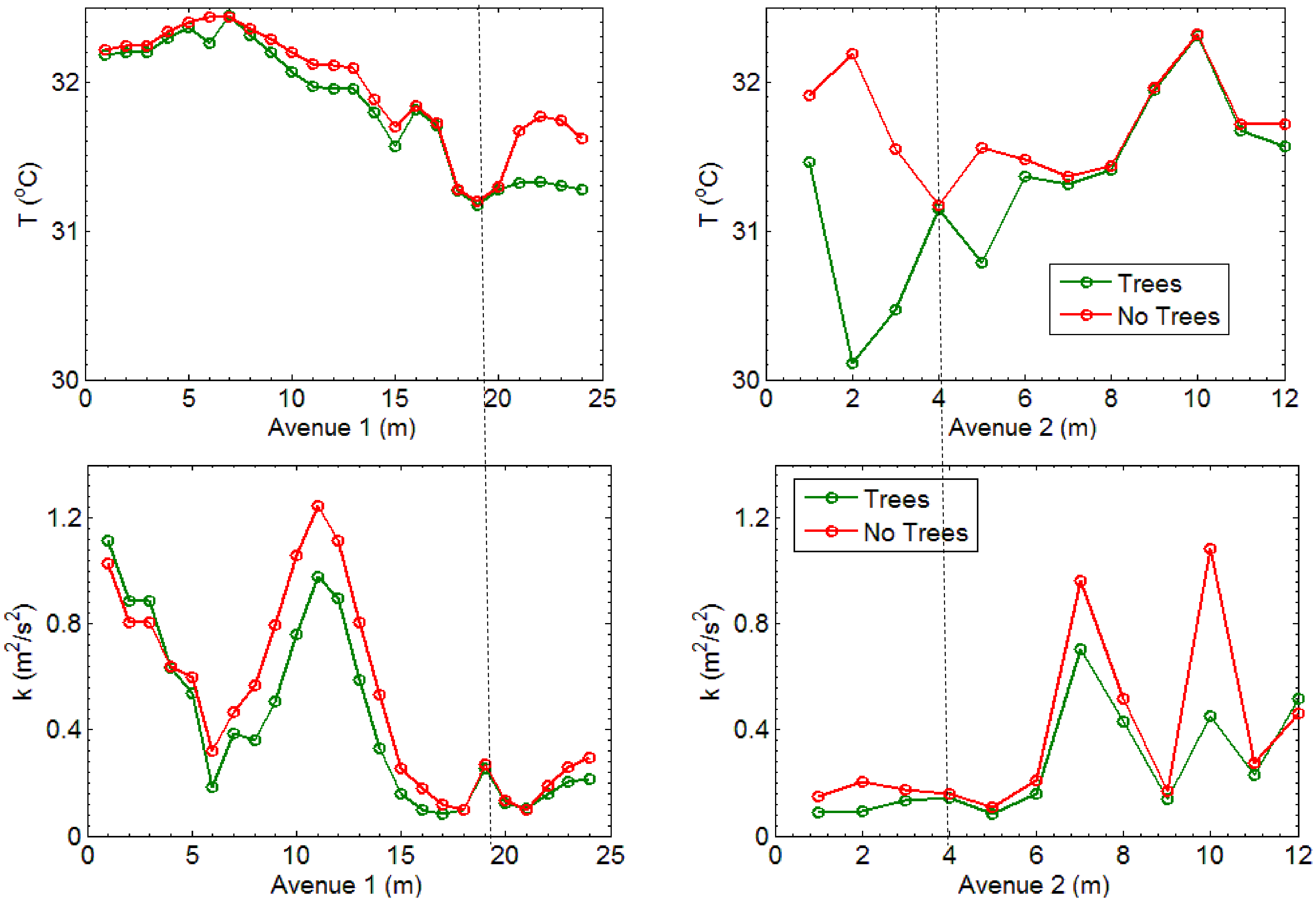
Avenue 1



Avenue 2



Temperature and TKE profiles along Avenues at z = 7m:



- Max. temperature reduction in presence of trees is ~ 2°C
- Is it due to lower turbulent kinetic energy ? May be or may not be!

Summary:

Type of flow	*Vegetation*	*Remarks*
Neutral	-	Good agreement between SC+ and OF
Unstable (constant T)	-	Weaker buoyancy in OF
Unstable (non-uniform heat flux)	-	Notable difference in flow and temperature distribution
Unstable (non-uniform heat flux)	yes	Temperature reduction of 2^{o}C.

Further work:

- Improve OF modelling for temperature/heat flux and vegetation.
- Incorporate features viz. shading of trees, anthropogenic heat flux
- Extend the computations to a district size and compare with field measurements.

Acknowledgements

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THANKYOU