Turbulence structure above a diabatically heated forest canopy composed of fractal Pythagoras trees

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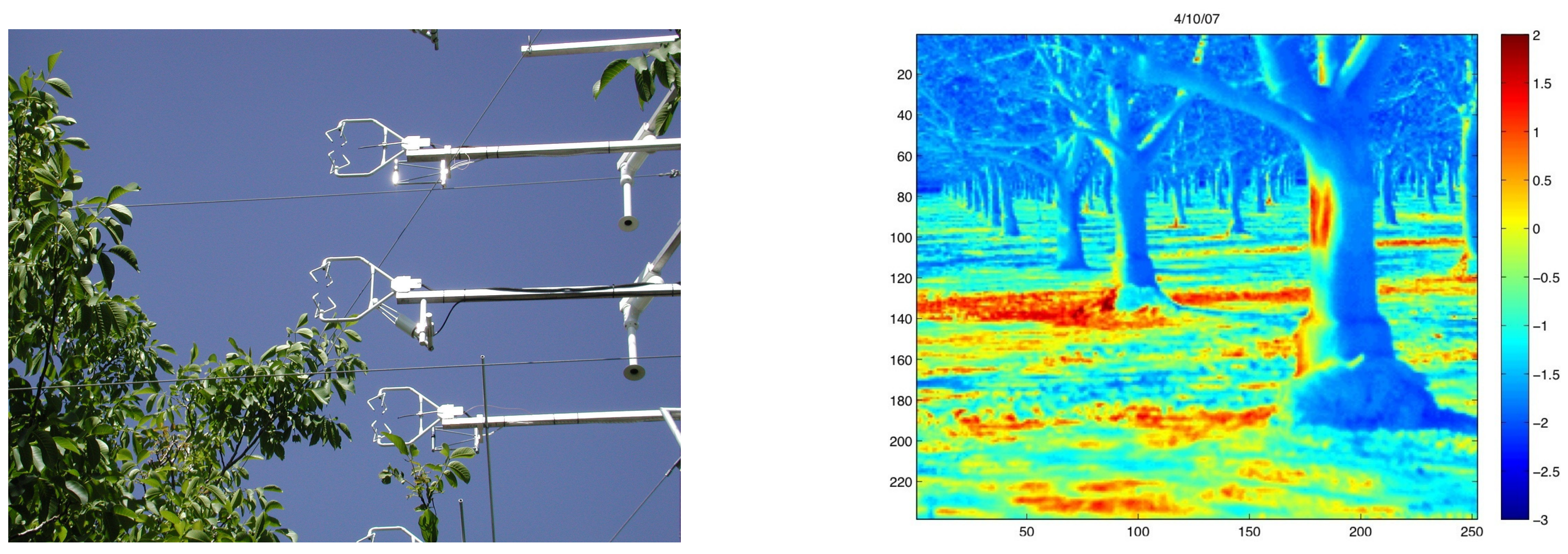
Motivation: Field campaigns

Exchange processes of e.g momentum, carbon dioxide (CO_2) or water vapor in forest canopies are **essentially multiscale**. The involved physics ranges from the scale of a leaf, where photosynthesis occurs, up to the height of the surface layer, where the largest eddies drive turbulent mixing.



http://www.eol.ucar.edu/deployment/field-deployments/field-projects/chats-project

Eddy covariance sensors in a walnut canopy (left) and infrared image of heated trees and trunk space (right) measure heterogeneities in the wind- and temperature field at a very small scale

Field-scale approach: Forest as a porous medium

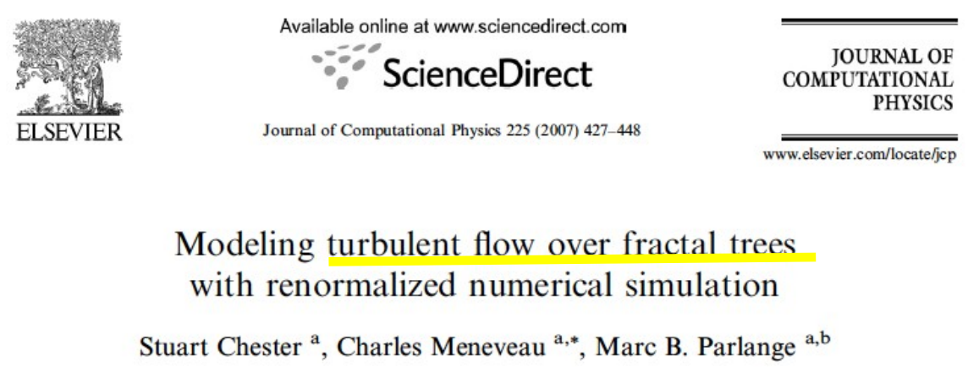
A pioneering large eddy simulation (LES) was conducted by Shaw and Schumann (1992), where they modeled *„the forest as a porous body of horizontally uniform* ***leaf area density: LAD(z)*** *with constant drag coefficient* c_D*“*

	Shaw & Schumann (BLM, 1992)	**Dupont & Brunet (JFM, 2009)**	**Finnigan, Shaw & Patton (JFM, 2009)**
ΔX	2 m	2 m	1 m
H	60 m	200 m	100 m
LAI	2, 5	2, 5	
T	10 min		2 hours

Is it possible to **bridge** the **gap** between small-scale measurements and field-scale simulations by state-of-the-art multiscale numerical simulations?

Plant-scale approach: Trees as fractal bodies

> *"Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line."*
> *(Mandelbrot, 1983)*



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Modeling turbulent flow over fractal trees with renormalized numerical simulation

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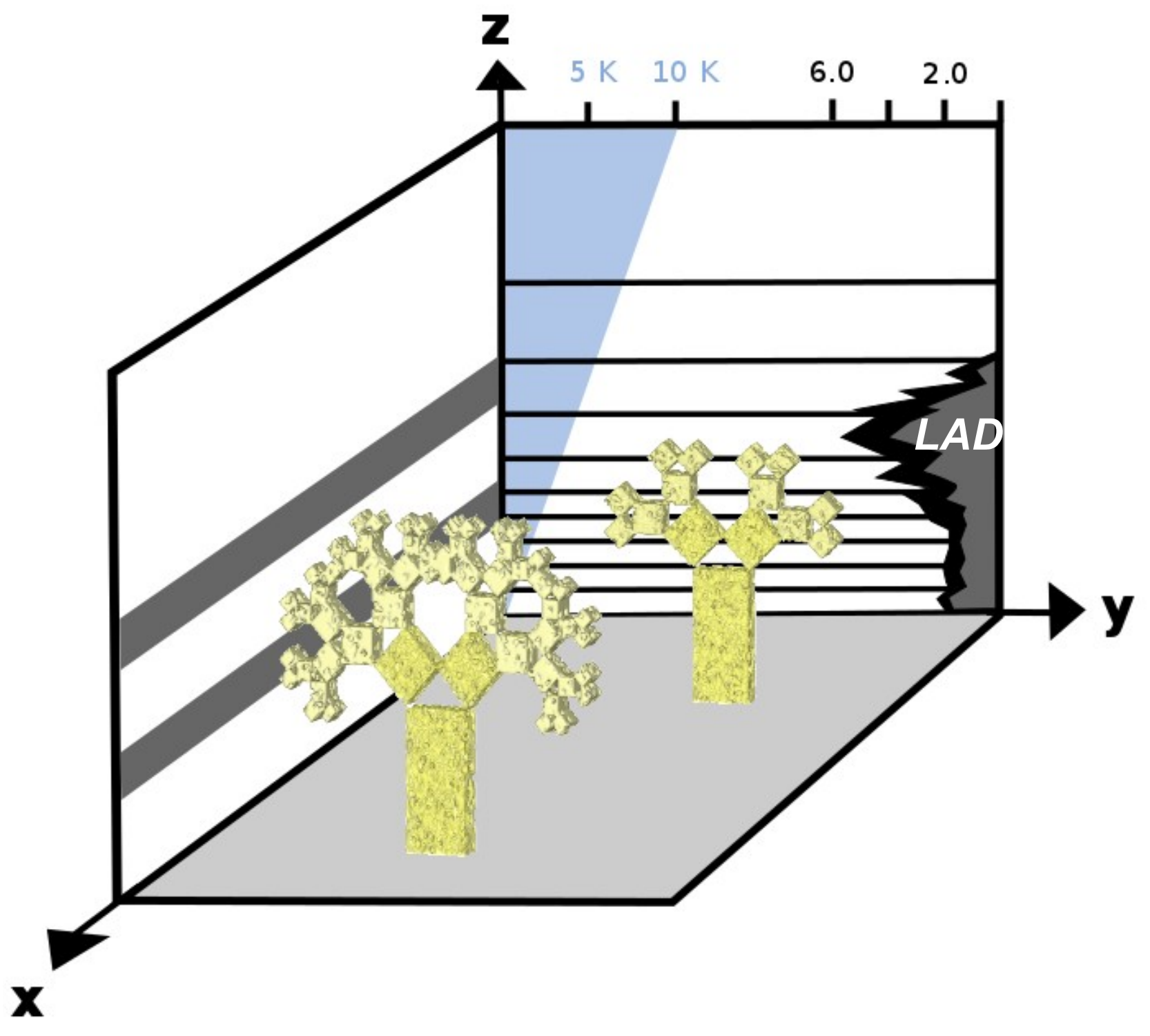


Other than Chester et all. (2007), we use: a **cluster** of **16 Pythagoras trees** with individual tree top, fractality, positions and a scale-dependent porosity.

Thermal stability of ambient air is prescribed on the flow as measured in experimental studies (Shaw 1988, Gao 1989)

Heated tree crown, as observed in field campaigns (EAGLE 2006, CHATS 2007). We use ΔΘ = 3.15 K.

Method: Heated immersed boundaries in EULAG

$$\nabla \bullet (\rho_b \mathrm{v}) = 0$$

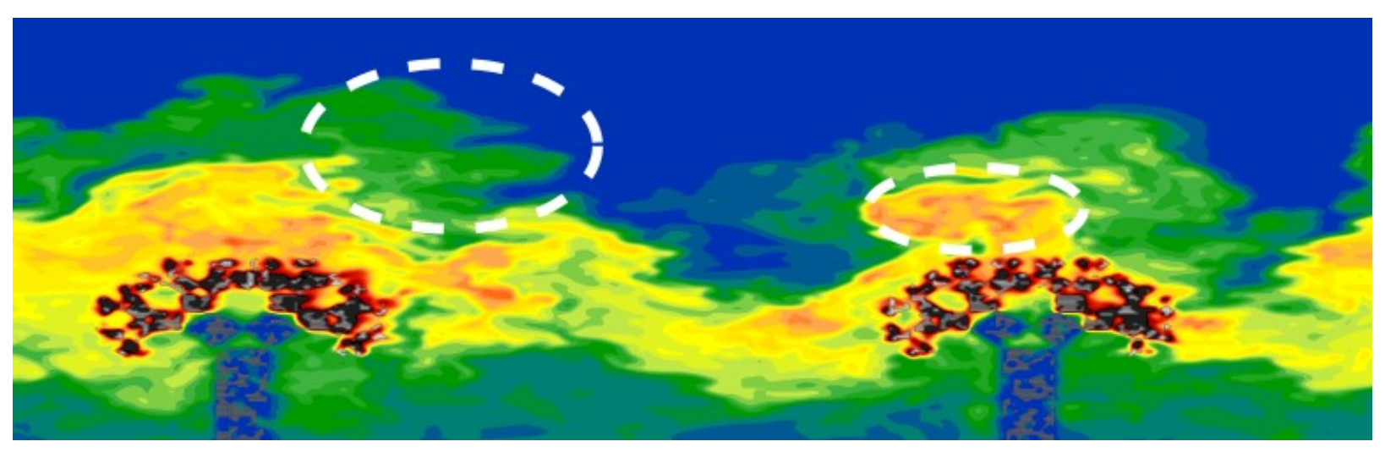
$$\frac{d\mathrm{v}}{dt} = -\nabla \pi' + \mathrm{g}\frac{\theta'}{\theta_b} + F' - \beta(\mathrm{v} - 0)$$

$$\frac{d\theta'}{dt} = H - \mathrm{v} \bullet \nabla \theta_e - \beta(\theta - \theta_c)$$

$$\psi' = \psi - \psi_e \qquad \psi = u, v, w, \theta, \ldots.. \qquad \pi' = \frac{p - p_e}{\rho_b}$$

We use the **Boussinesq approximation** in EULAG (Prusa, et al. 2008) with immersed boundaries to explicitly resolve the Pythagoras trees.

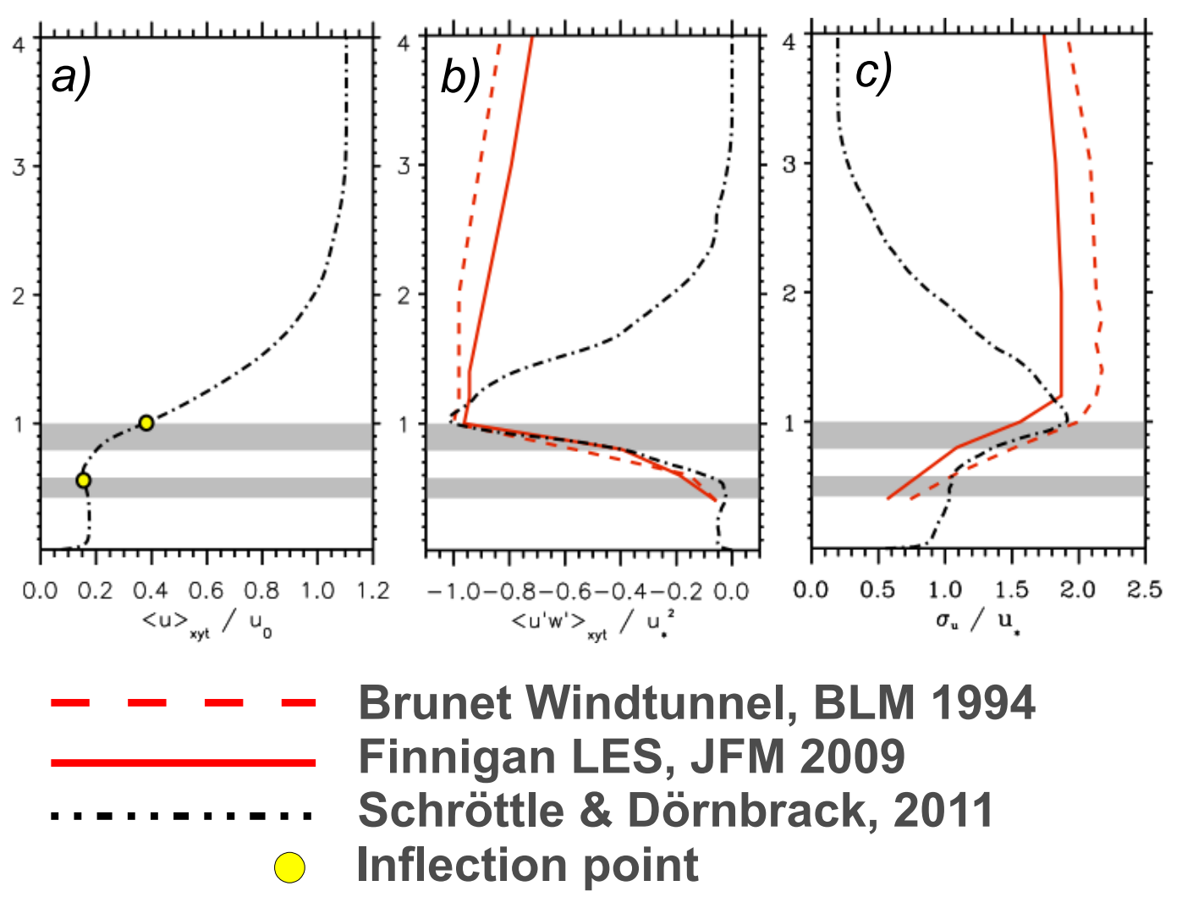
ρ_b = 1.025 kg/m^3
Θ_b = 300 K
p_b = 1000 hPa
$\Theta_c = \Theta_e$ + 3.15 K (tree crown)



This is an extension to work by Smolarkiewicz et al. (2007) and the first time that **immersed boundaries** are used to prescribe a certain temperature on the flow in EULAG.

„EULAG, a computational model for multi-scale flows“, Prusa et al. 2008

Results: Neutral reference run



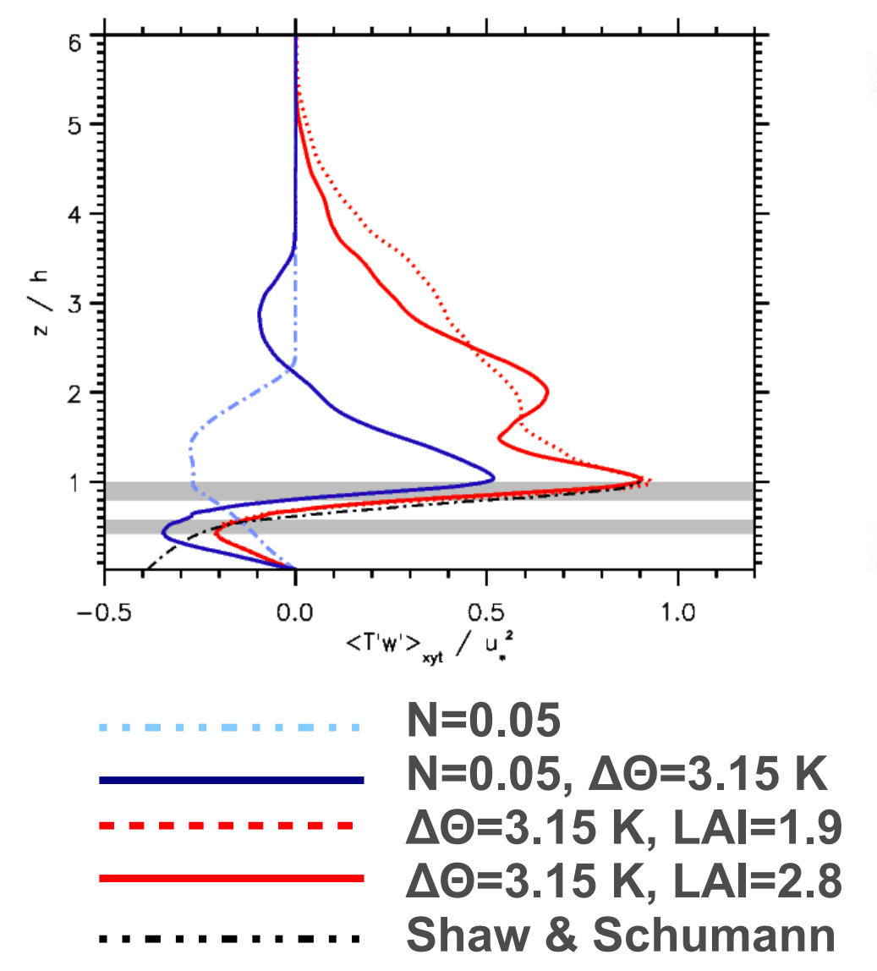
Comparison of neutral reference run with former **field-scale simulations**:

The **velocity profile** (a) agrees qualitatively with Shaw & Schumann (1992). An **inflection point** arises as in a mixing layer profile.

Momentum flux (b) coincides very well inside the forest canopy with LES by Finnigan, Shaw & Patton.

Diabatic Effects

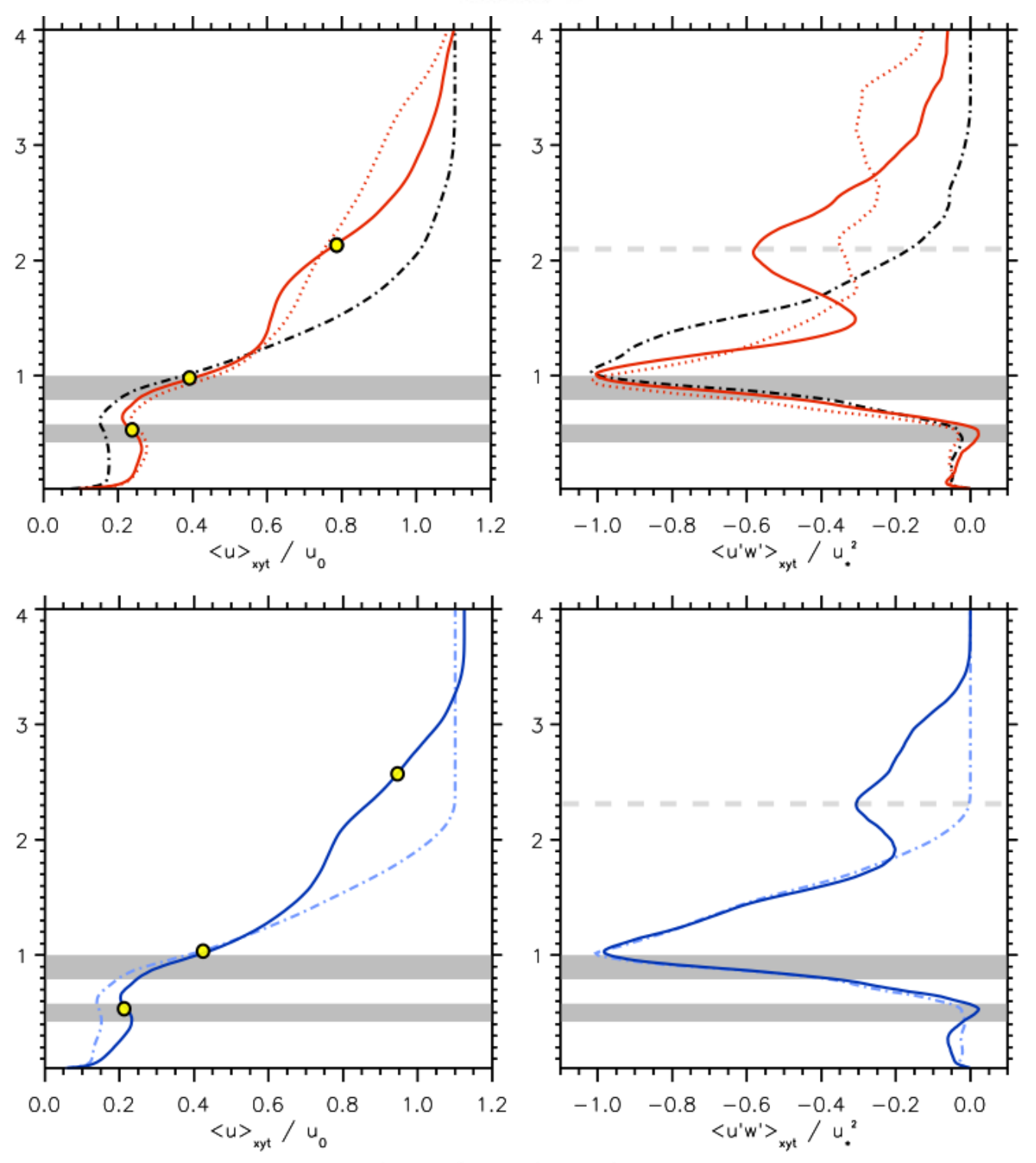
Heat Flux



Heat flux in heated run agrees quantitatively with a **parametric model** used by Shaw & Schumann.

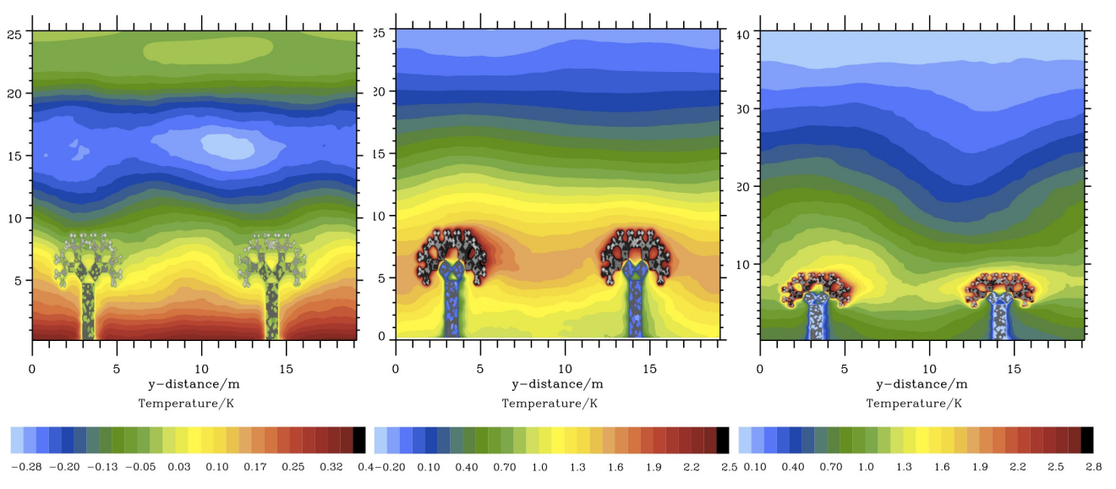
Velocity Profile

Horizontal velocity **increases** in the trunk space, when the crown is heated. **Inflection** points **intensify**. Internal **boundary layer (IBL) height** increases.

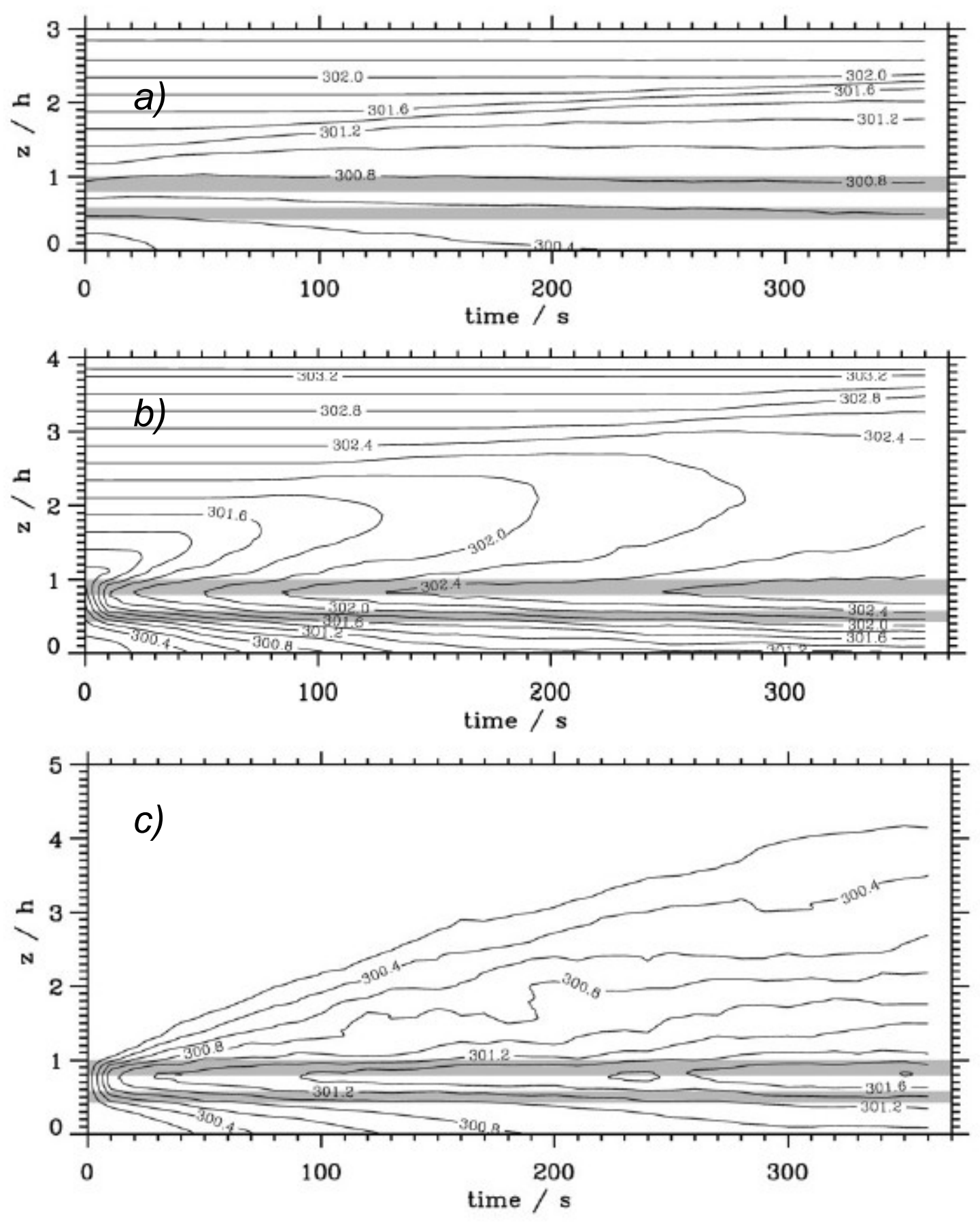


Mean Temperature

Typical patterns evolve in the temperature field, **ramps of cold air** accumulate above the trees in the stable run as found in a field experiment by (Gao & Shaw, 1989)



Temperature



The evolution of the temperature profile is depicted as **Hovmoeller** diagrams for various stratifications:

a) stable
b) stable + heated
c) neutral + heated

An **unstable stratification** evolves *(b, c)* above the trees and a **stable one below**.

Momentum Flux

Shape of profile inside the canopy does not depend on the heated crown.

Interestingly, further **shear layers** evolve above the canopy top that depend on **LAI.**

The friction velocity **u***⁎* increases significantly due to **diabatic heating**.

Conclusions

Our setup with fractal Pythagoras trees provides a forest canopy structure with ***LAD(z)*** of **realistic complexity** (Schlegel, Metstroem Conference Berlin 2011)

Multiscale flow simulation over a wide range of scales (100 m **surface Layer**, 10 m **tree** height and 5 cm as a scale of smaller **branches**) is possible in **EULAG**

Neutral reference run with fractal plant-scale approach shows a **similar turbulence statistics** as former **field-scale simulations** (Finnigan et all. 2009)**.**

The friction velocity **u***⁎* as crucial parameter (Bohrer, 2007) is observed: diabatic heating increases **u***⁎* significantly, further **shear layers** above canopy evolve, **internal boundary layer (IBL) height rises**

Outlook

Comparison of results for diabatic flow with recent **field experiments** (Patton, CHATS)

Extension to **multiphase flow** and **moist processes** (Smolarkiewicz, NCAR)

Solution adaptive mesh to **increase resolution** to leaf-scale (Kühnlein, LMU)

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