LARGE-EDDY SIMULATIONS OF A WIND TURBINE WAKE ABOVE A FOREST

Josef Schröttle[a,c], Zbigniew Piotrowski[b],
Thomas Gerz[a], Antonia Englberger[a], Andreas Dörnbrack[a]

a Institute for Atmospheric Physics,
German Aerospace Center (DLR),
Oberpfaffenhofen, Bavaria, Germany

b Institute of Meteorology and Water
Management (IMGW), Warsaw, Poland

c Ludwig-Maximilians-Universität,
Department of Physics, Munich, Germany

I. From fractal tree canopy turbulence ...

   a) Meassurements at Plant Scale

   b) Immersed Boundaries

II. … to large-eddy simulations of forest canopy boundary layers ...

   a) Challenges to overcome

   b) Modeling a Forest Canopy

   c) Tow Hydrodynamic Solvers

III. … with wind turbine wake flow.

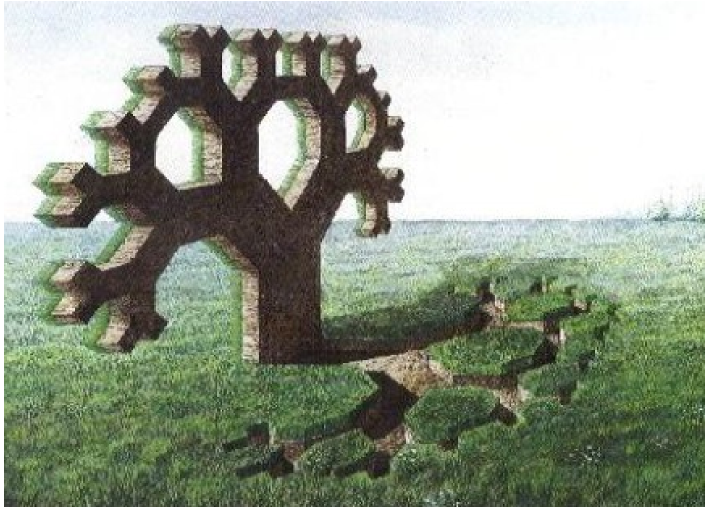
   a) Velocity Deficit

   b) Momentum Transport

   c) Turbulent Kinetic Energy

   d) Turbulence Intensity

   e) Eddy dissipation Rate



Pythagoras tree (above) and wind turbines w/ a forest (below)

I) EULAG, LES with Immersed Boundaries

$$\nabla\cdot\boldsymbol{v} = 0$$

$$\frac{d\boldsymbol{v}}{dt} = -\nabla\frac{p'}{\rho_b} - \boldsymbol{g}\frac{\theta'}{\theta_b} + \boldsymbol{D}^{\boldsymbol{v}} \underline{-\beta(\boldsymbol{v}-\boldsymbol{v}_F)}$$

$$\frac{d\theta'}{dt} = \boldsymbol{v}\cdot\nabla\theta_e + \boldsymbol{D}^{\theta} \underline{-\beta(\theta-\theta_F)}$$

$$\frac{de}{dt} = S(e) \underline{-\beta(e-e_F)}$$

Boussinesq Approximation

$\rho_b = 1.025\ \mathrm{kg/m^3}$

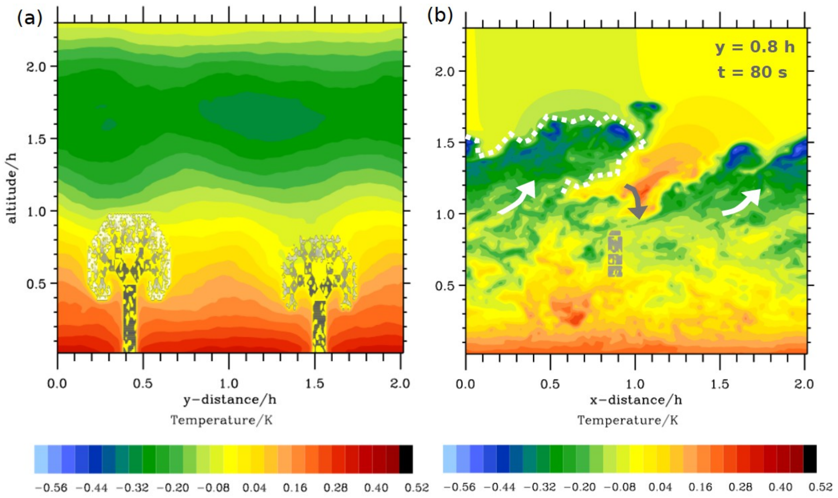
$\Theta_b = 300\ \mathrm{K}$

$p_b = 1000\ \mathrm{hPa}$

$\Theta_F = \Theta_e(z) + 3.15\ \mathrm{K}$

Immersed Boundaries

$\underline{\beta = 2/dt \text{ and } 0 \text{ outside forest}}$



Imrsb. w/ a prescribed temp. are an extension to the ones used for 'Building resolv. LES & comparison with windtunnel studies' (Smolarkiewicz et al. JCP 2007)

'Turbulence structure in a diabatically heated forest canopy composed of fractal Pythagoras trees' (Schröttle and Dörnbrack TCFD 2013)

Turbulence from the ground over a scale of 0.1 m up to 100 m with **cyclic** horiz. boundaries.

II) Forest Parameterization

Is it possible to resolve the **turbulence structure** correct over such a wide range of scales with realistically sized **wind turbines** by state-of-the-art **multiscale numerical simulations?**

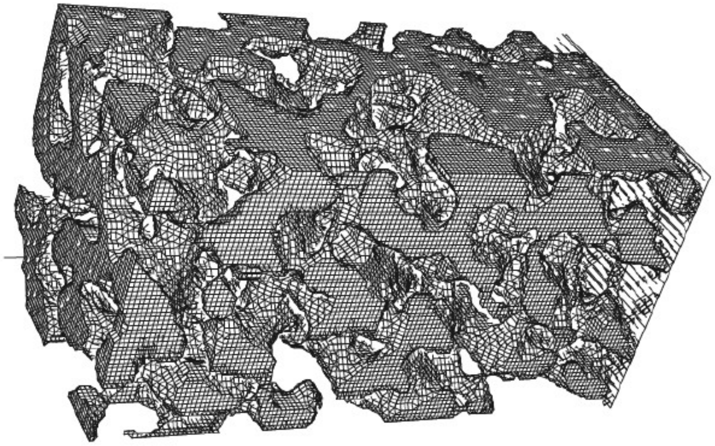
X Scales range from 10 cm of canopy elements to the domain length of 1 km. → n = 10000
Currently, this is computationally very demanding !

X Three dimensional fields of the real porosity of various forests are rarely available !

II) Field-Scale Approach

„Forest as a **porous body** of horizontally uniform **leaf area density:** ***LAD(z)*** with constant drag coefficient c_{for}."

(Shaw & Schumann 1992)



$$\boldsymbol{F}_{\boldsymbol{D}} = -c_{for}\, a(z)\, V\, \boldsymbol{v}$$

Field-scale simulations, where resolution is of $O(1\,m)$

- Shaw & Schumann (1992)
- Dupont & Brunet (2009)
- Finnigan, Shaw & Patton (2009)
- Schlegel et al. (2012, 2014)
- Nebenfür & Davidson (2015)
- Patton et al. (2016)

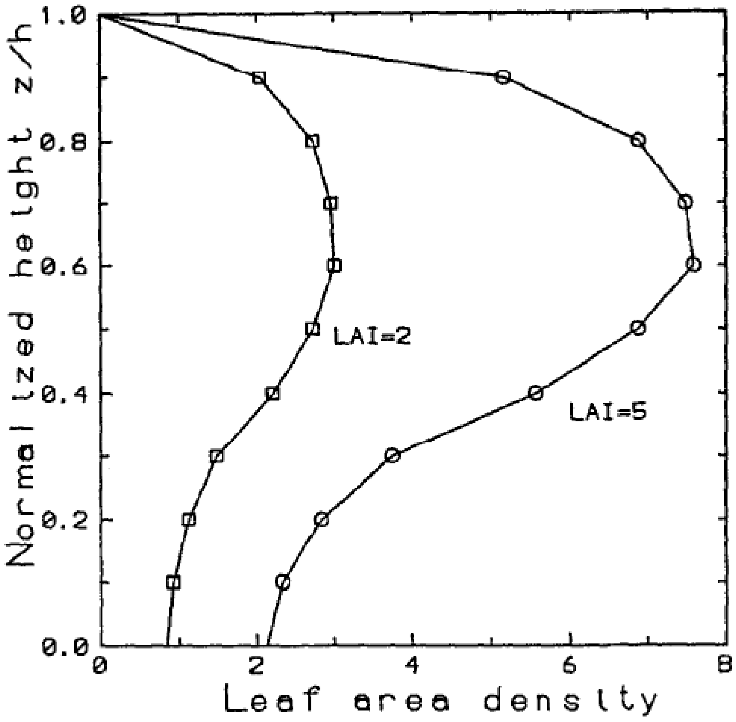
II) Forest Parameterization

neutral	convective	stable
Bohrer et al. (2009) Dupont & Brunet (2011) **IMB** Dörnbrack (2008) Finnigan et al. (2009) Kanani et al. (2015) Schlegel et al. (2012, 2014) Shaw & Patton (2003) Shaw & Schumann (1992) Nebenf. & Davidson (2015) Lopes et al. (2015)	Bohrer et al. (2009) Kanani et al. (2015) Shaw & Schumann (1992) Nebenf. & Davidson (2015) Patton et al. (2016) simulations	Kanani et al. (2015) **IMB** Schröttle & Dörnbrack (2013) Nebenf. & Davidson (2015)
Brunet et al. (1994) Shaw (1988) Kanani et al. (2015) observations	Bohrer (2009) Kanani et al. (2015)	Gao (1989) Shaw (1988) Arnqvist et al. (2015) Kanani et al. (2015)

II) Concept of Leaf Area Density

Idealized 1 D

h = 20 m in the paper by
Shaw & Schumann (BLM 1992)

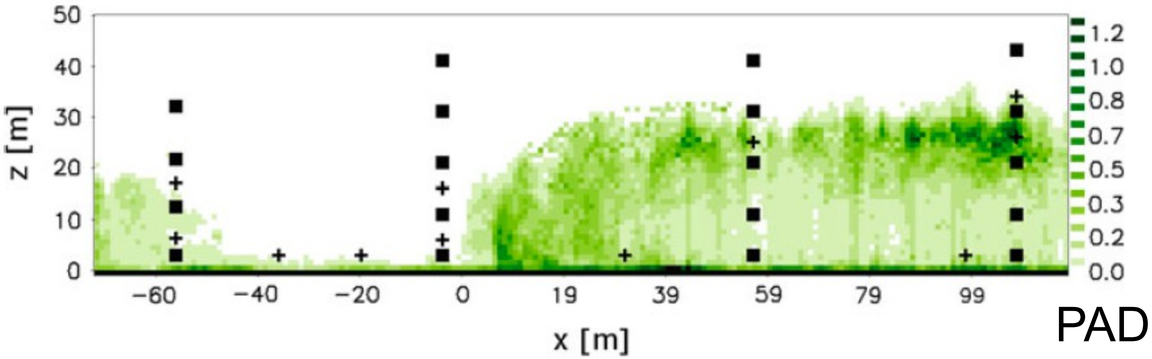


$$a(z)h$$

Measured 3 D

Schlegel et al. (BLM 2012, 2014)

Probability area density (x, y, z)



[PAD] = m² / m³

II) Turbulence Upstream of the Wind Turbine

Is it possible to resolve the **turbulence structure** correct **in the inflow** of one realistically sized **wind turbine** by state-of-the-art **multiscale numerical simulations?**

✓ The forest can be simulated by using the Shaw & Schumann (1992) forest parameterization.

✓ Three dimensional fields of the real porosity of various forests furthermore exist and can be the basis for large-eddy simulations !

✗ The simulation can not run in cyclic boundary conditions as in forest flow studies (Dupont and Brunet, JFM 2009) as the wake extends over ***20** diameters **D** in streamwise direction*

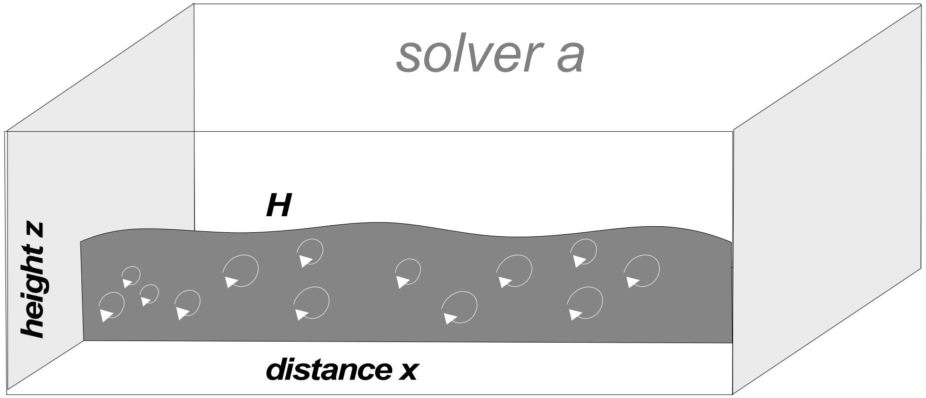
WAKE STRUCTURE IN TURBULENCE

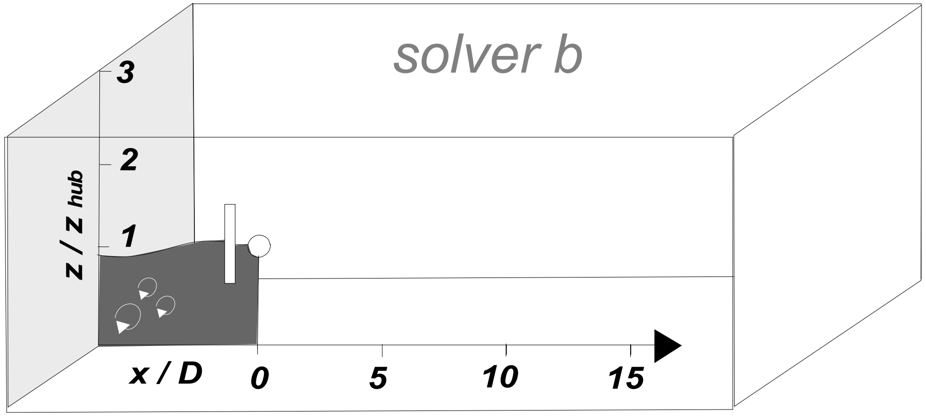
How should we model the turbulent inflow in large-eddy simulations?

Paper for *Torque 2016* Conference in Munich, October (2016)

Neutral plane wall boundary layer turbulence ...

… with a **wind turbine**.





cyclic boundaries

open boundaries

II) EULAG, Large-eddy Simulation

With two hydrodynamic flow solvers: *a & b*

$$\nabla \cdot \mathbf{v}^{a,b} = 0$$

$$\frac{d\mathbf{v}^{a,b}}{dt} = -\nabla \pi^{a,b} + \mathbf{D}(v^{a,b}) - \underline{c_{for}\, a V^{a,b} \mathbf{v}^{a,b}} + \underline{\mathbf{F}^{b}_{turbine}}$$

$$\frac{d e^{a,b}}{dt} = S(e^{a,b}) - \underline{2\frac{e^{a,b}}{\tau}}$$

Boundary Conditions

a) cyclic
b) **open**

Forest Shaw & Schumann (1992)

$\tau = (c_{for}\, a V)^{-1}$ as time scale $[\tau]$ = s

$a(z)$ as leaf area density $[a]$ = m² / m³

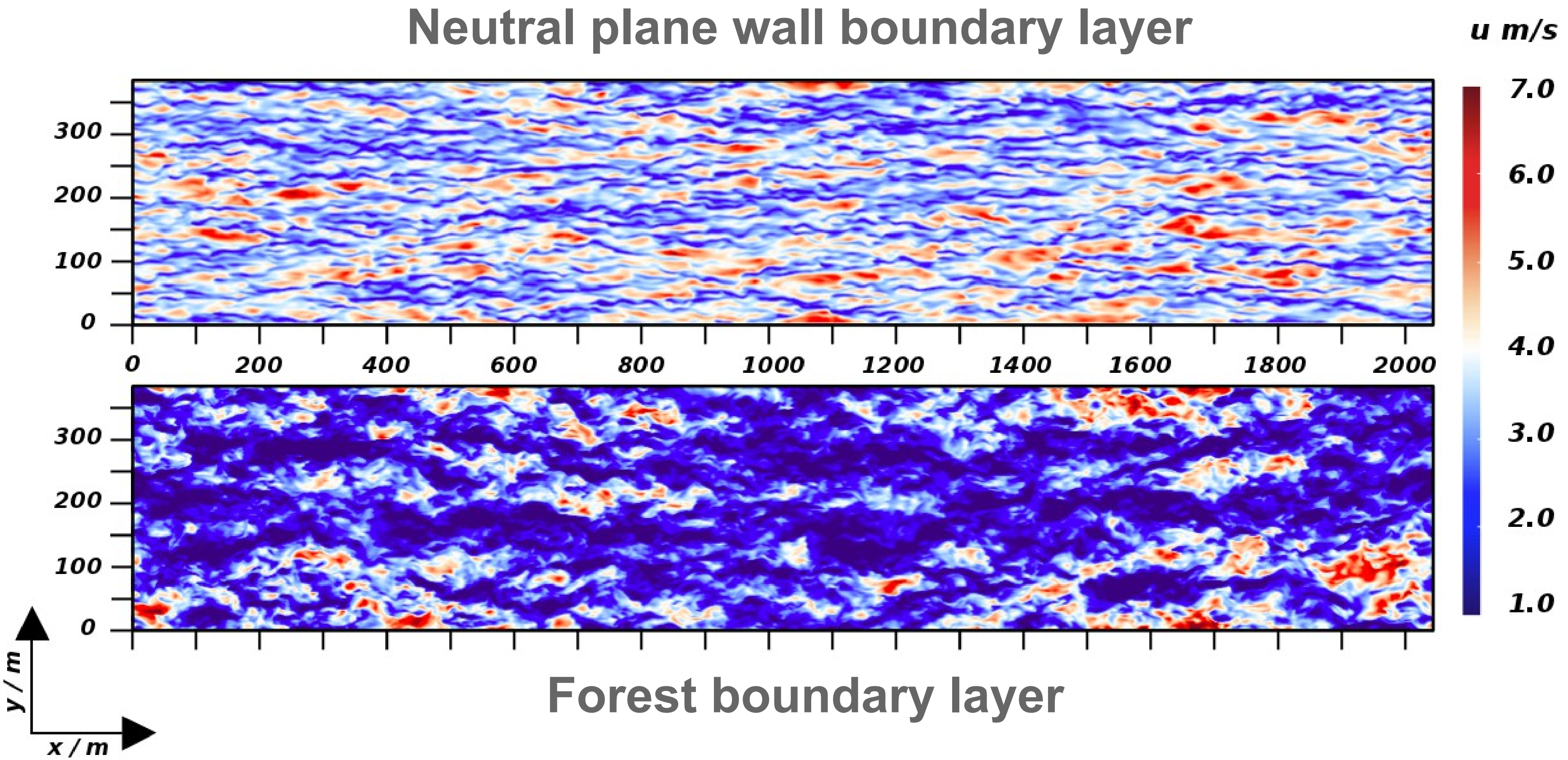
$V(x,y,z,t) = (u^2+v^2+w^2)^{1/2}$ as scalar velocity

Wind turbine

$$\underline{\mathbf{F}^{b}_{turbine}} = -\mathbf{e}_x c_D U^2/\Delta x$$

III) Turbulence Structure

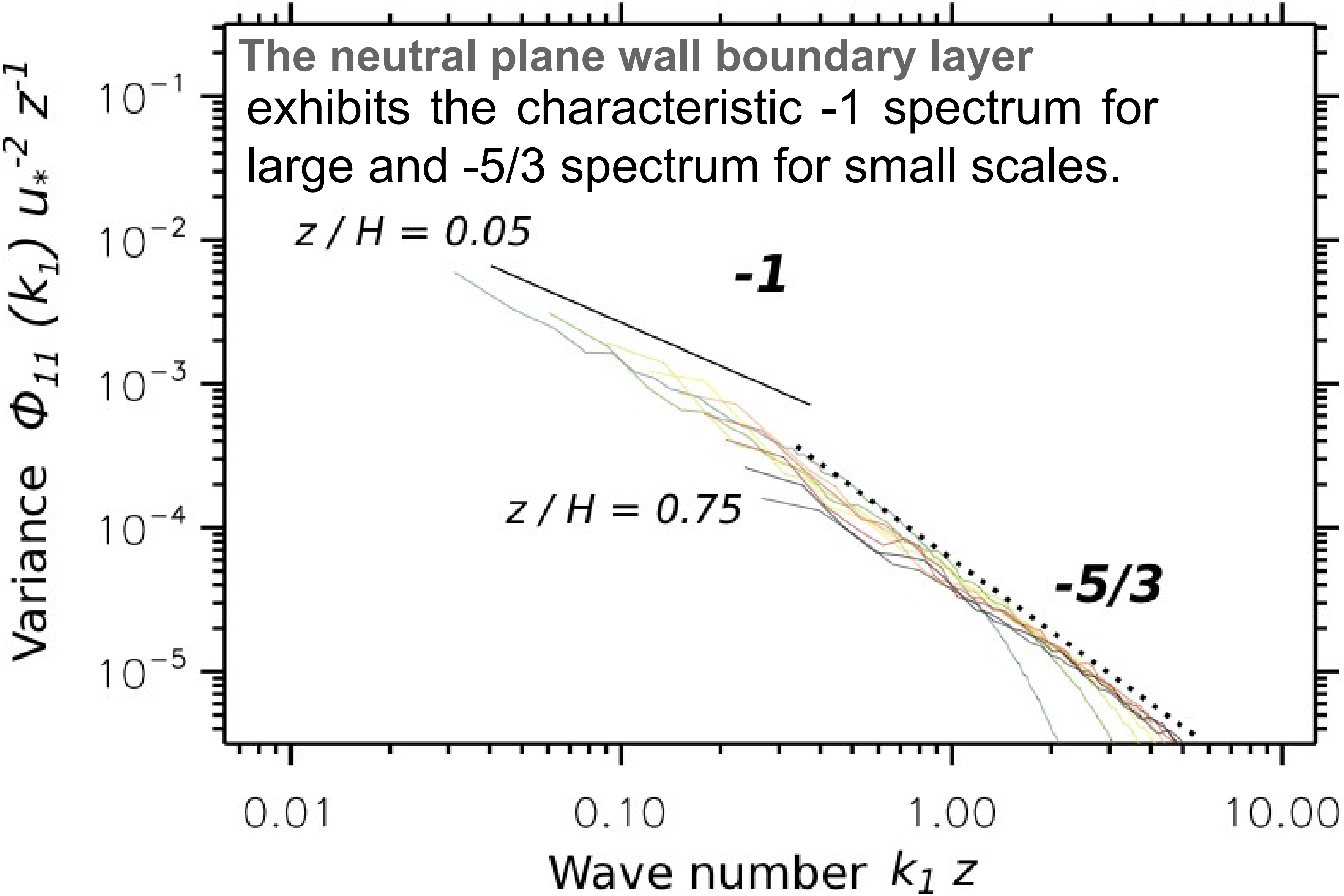
Instantaneous Streamwise Velocity *u(x,y)*



Horizontal fields 2 m above the ground / forest canopy reveal coherent streaks of low momentum of different shape and magnitude.

III) Turbulence Structure

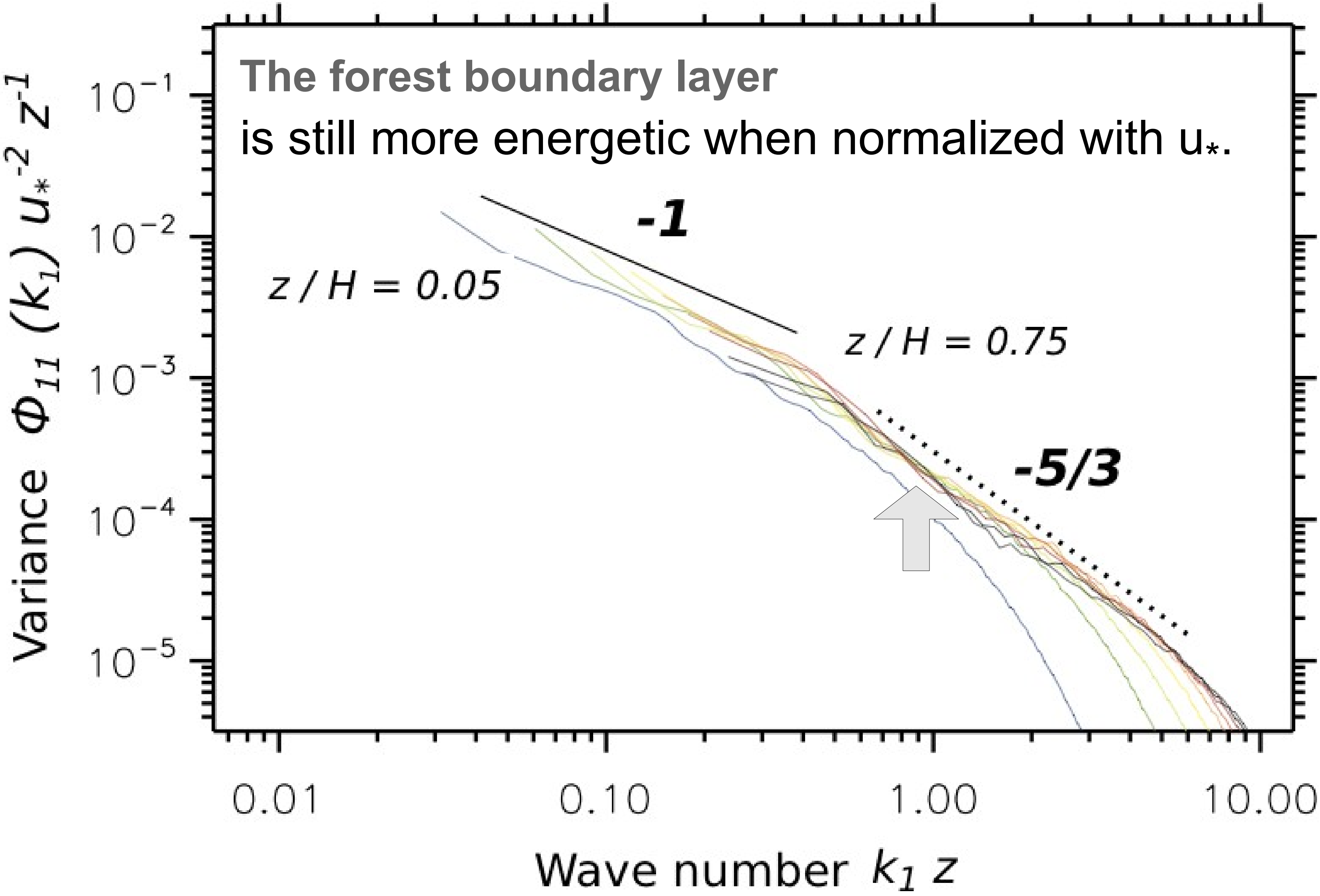
Fourier Analysis



The neutral plane wall boundary layer exhibits the characteristic -1 spectrum for large and -5/3 spectrum for small scales.

III) Turbulence Structure

Fourier Analysis

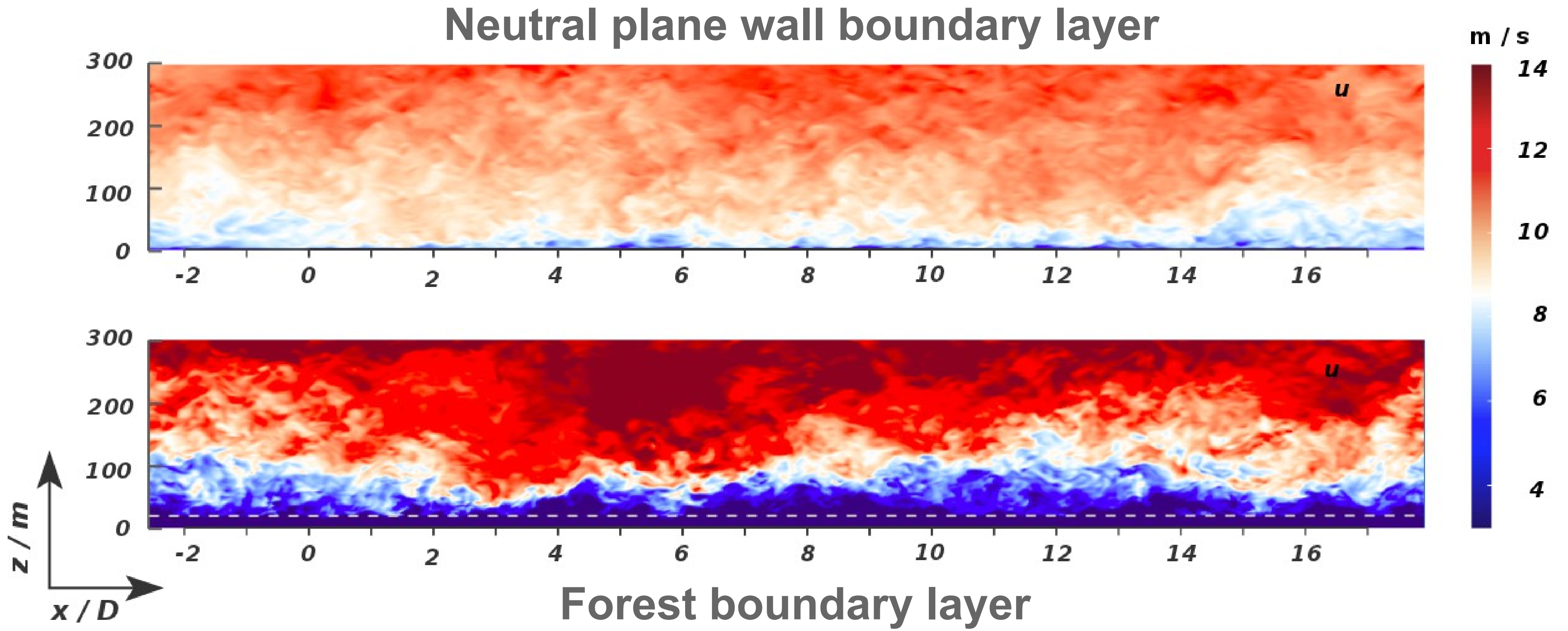


The forest boundary layer

is still more energetic when normalized with u*.

III) Turbulence Structure

Instantaneous Streamwise Velocity *u(x,z)*

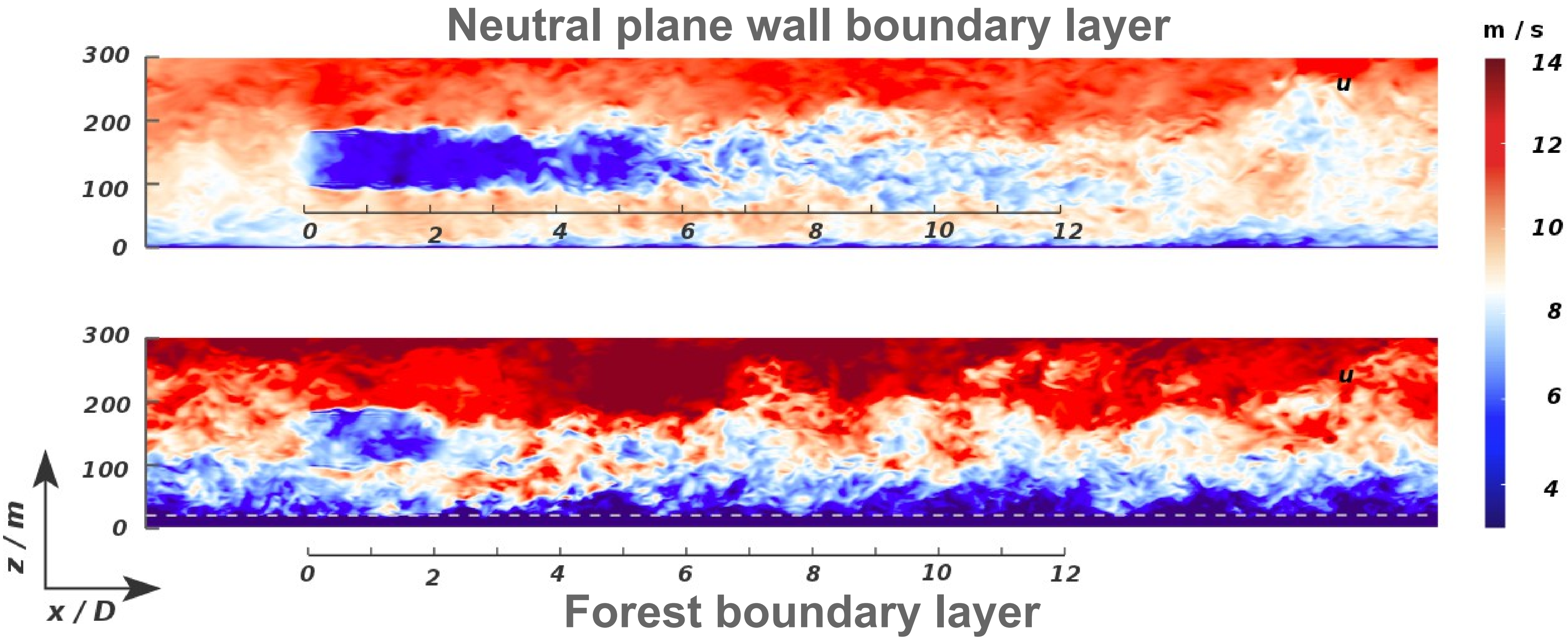


Neutral plane wall boundary layer

Forest boundary layer

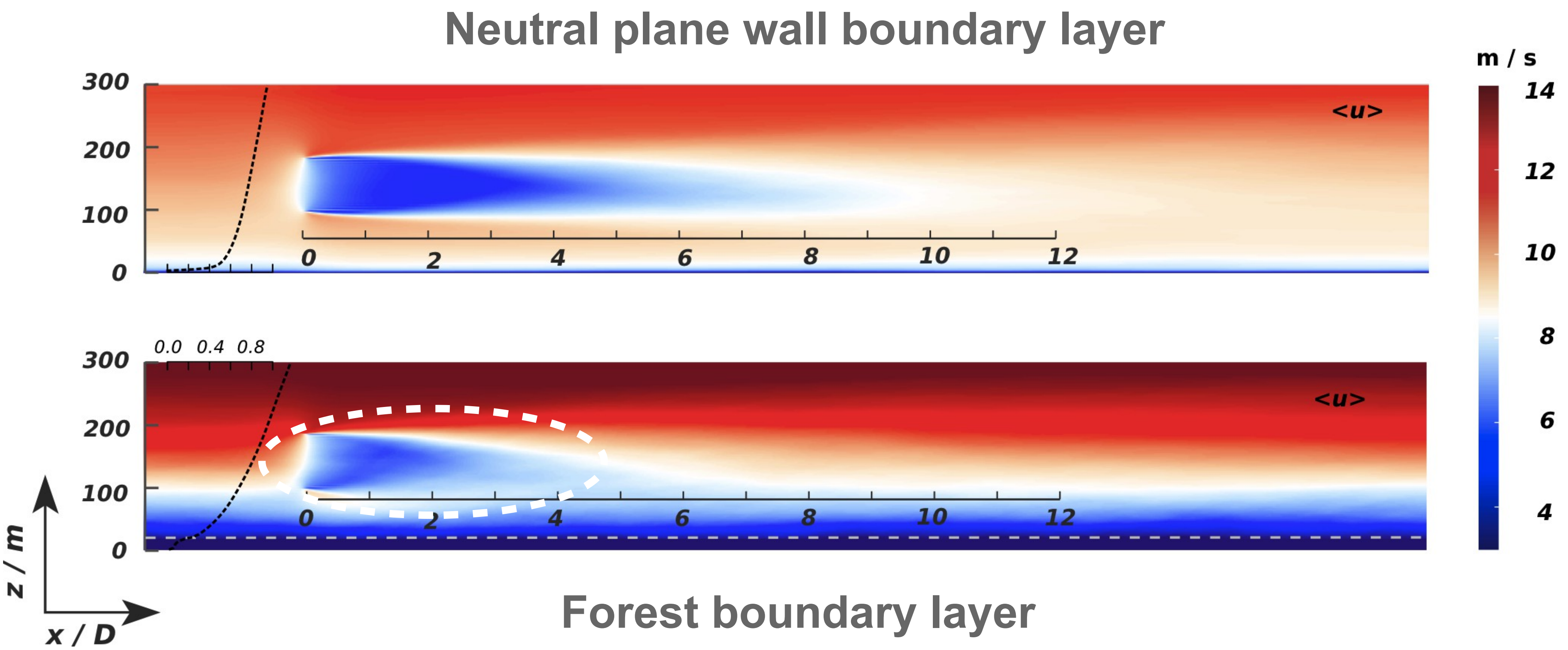
III) Turbulence Structure

Instantaneous Wake Structure



III) Wake Structure

Mean Streamwise Velocity <*u(x,z)*>

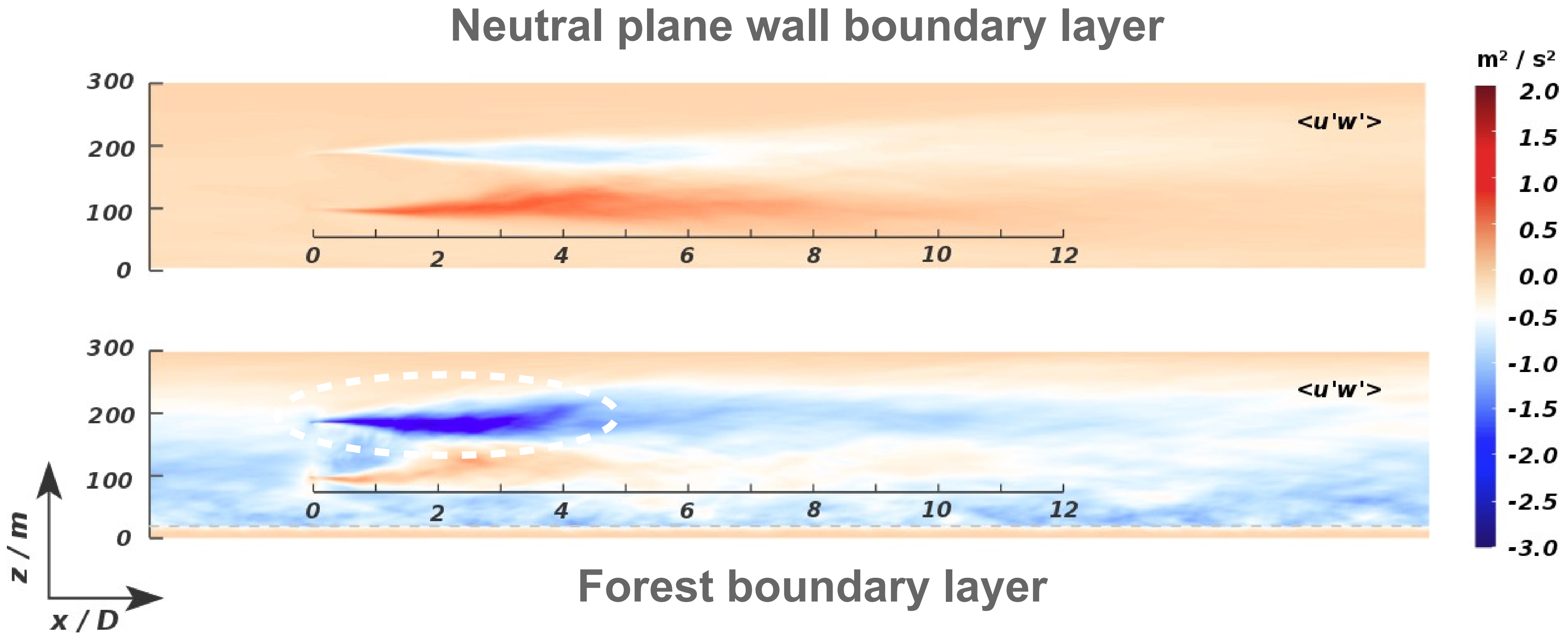

Neutral plane wall boundary layer

Forest boundary layer

The wind turbine wake recovers over a shorter distance above the forest.

III) Wake Structure in the Mean

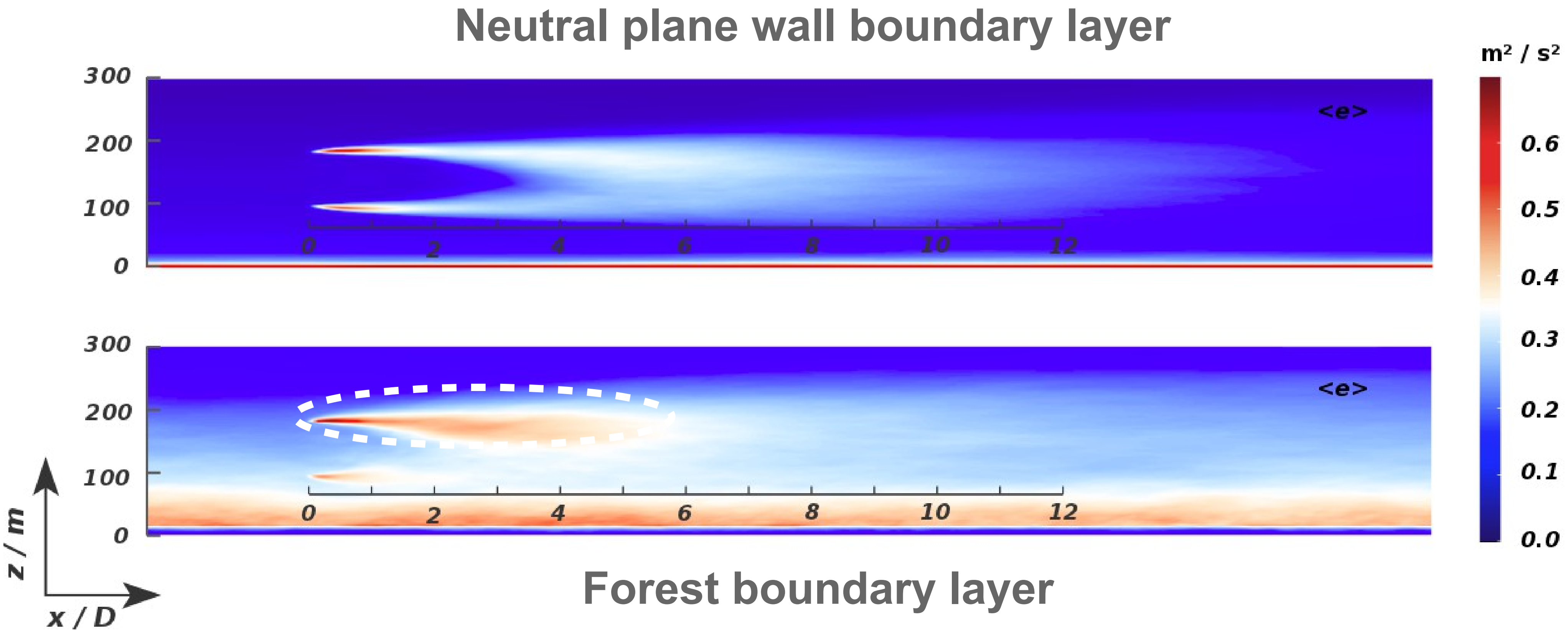
Mean Momentum Flux <*u'w'*>



The momentum flux is stronger above the forest.

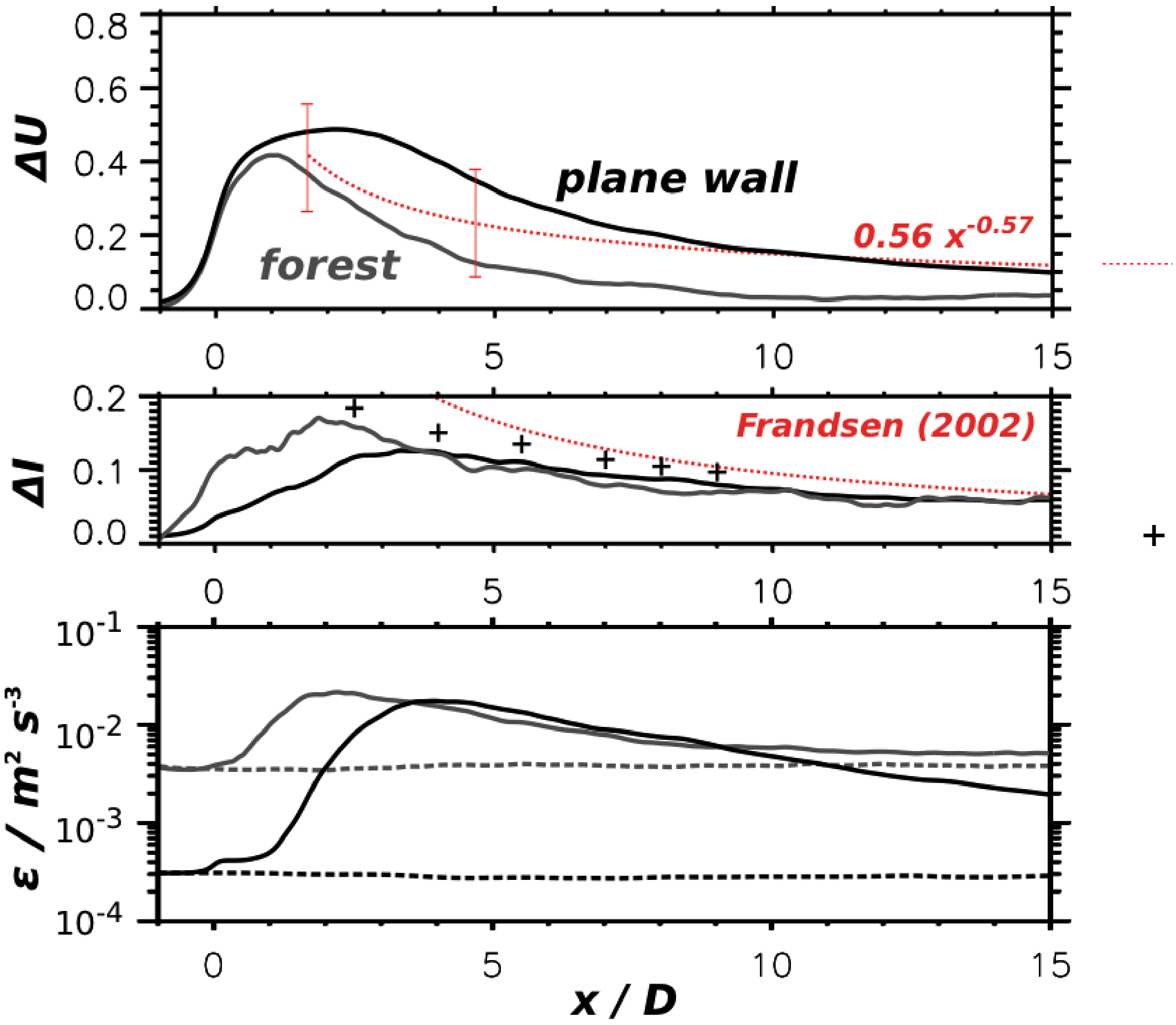
III) Wake Structure in the Mean

Subgrid scale Turbulent Kinetic Energy <e(x,z)>



The wind turbine wake is asymmetric above the forest.

PROPERTIES OF WAKE QUANTITIES & TURBULENCE



Velocity deficit

$$\Delta U = \frac{U_{hub} - U}{U_{hub}}$$

Aitken et al. (2014b)

Added Turbul. Intensity

$$\Delta I = \sigma_{u,m} \; / \; U$$

+ LES by Jimenez et al. (2007)

Eddy Dissip. Rate

$$\epsilon = <e>^{3/2} \; / \; dz$$

range agrees with measurements by Lundquist (2015)

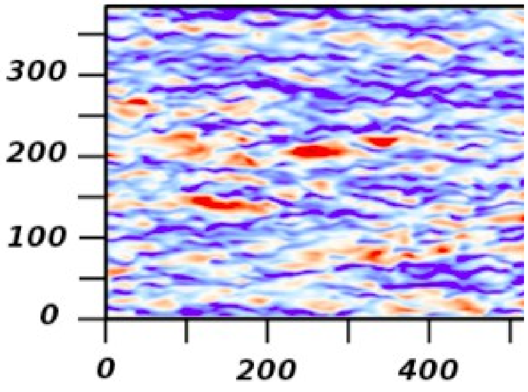
IV) Conclusions from Large-eddy Simulations of a Wind Turbine Wake above a Forest

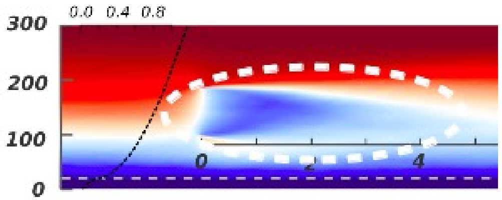
(1) The **two hydrodynamic solvers** were **successfully applied** in EULAG.

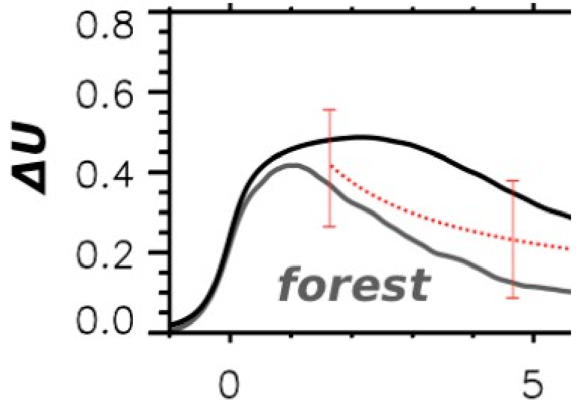
(2) **Various kinds of atmospheric turbulence** can be simulated upstream of a wind turbine.

(3) The earlier recovery of the wake velocity deficit ***ΔU*** above the forest allows the conclusion that more wind energy can be harvested by the cost of higher loads on the wind turbine blades above the forest.

(4) Wind turbine wake flow was simulated for the **first time with LESs** above a forest.







Thank you for your attention!