Edge flow in inhomogeneous canopy

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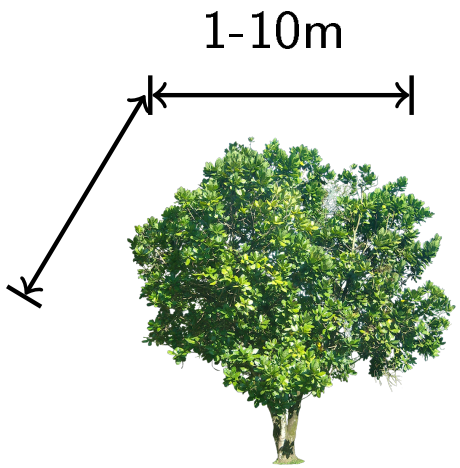
Motivation

- Most of knowledge on forest edge flows : numerical and wind-tunnel experiments where canopy **horizontally homogeneous**
- Differences in **inhomogeneous** canopy ?
  (3D tree-scale heterogeneities)

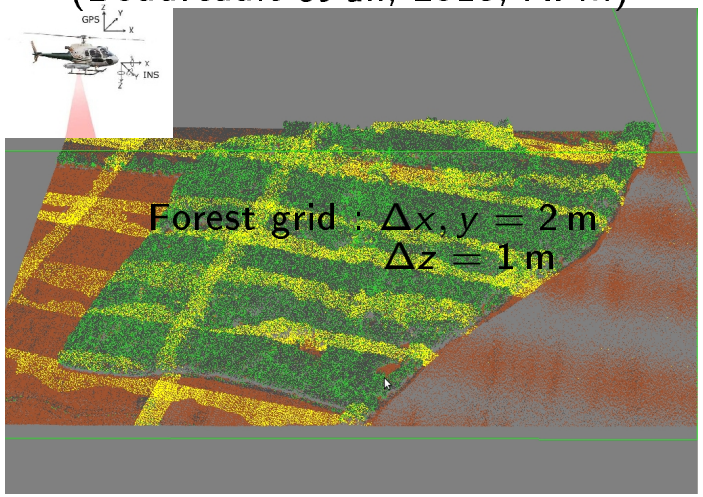


Edge site

Helicopter-based high resolution scans ($> 10\ \mathrm{returns/m^2}$) $\rightarrow$ LES input

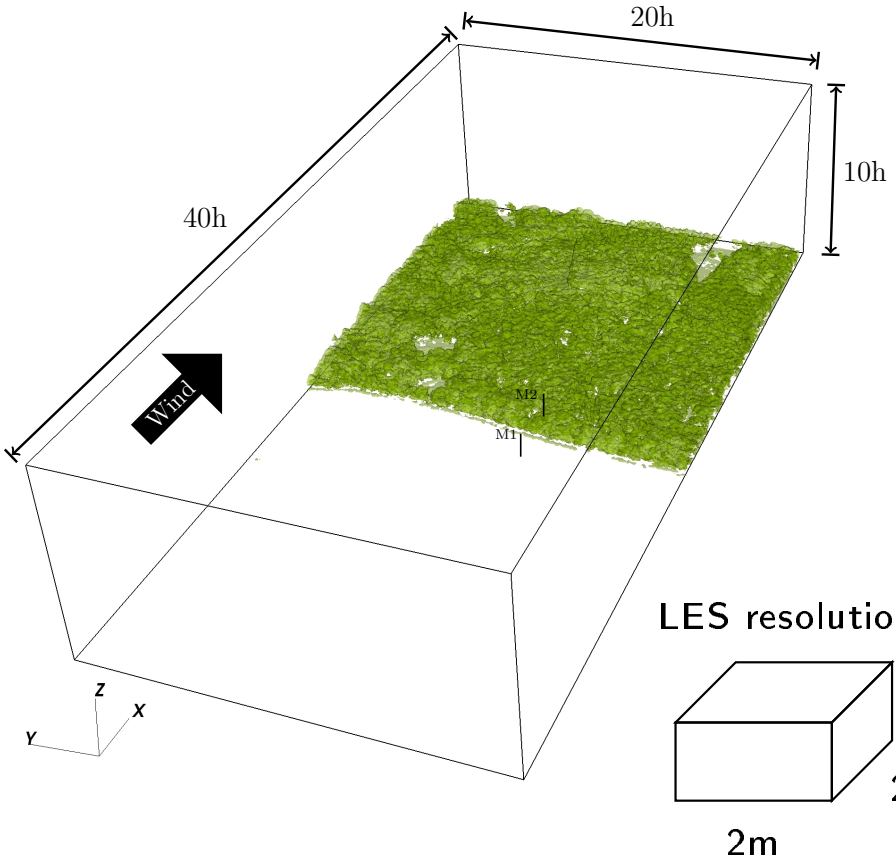
(Dellwik *et al.*, 2014, *QJRMS*)

(Boudreault *et al.*, 2015, *AFM*)



Neutral flow

Domain



LES model

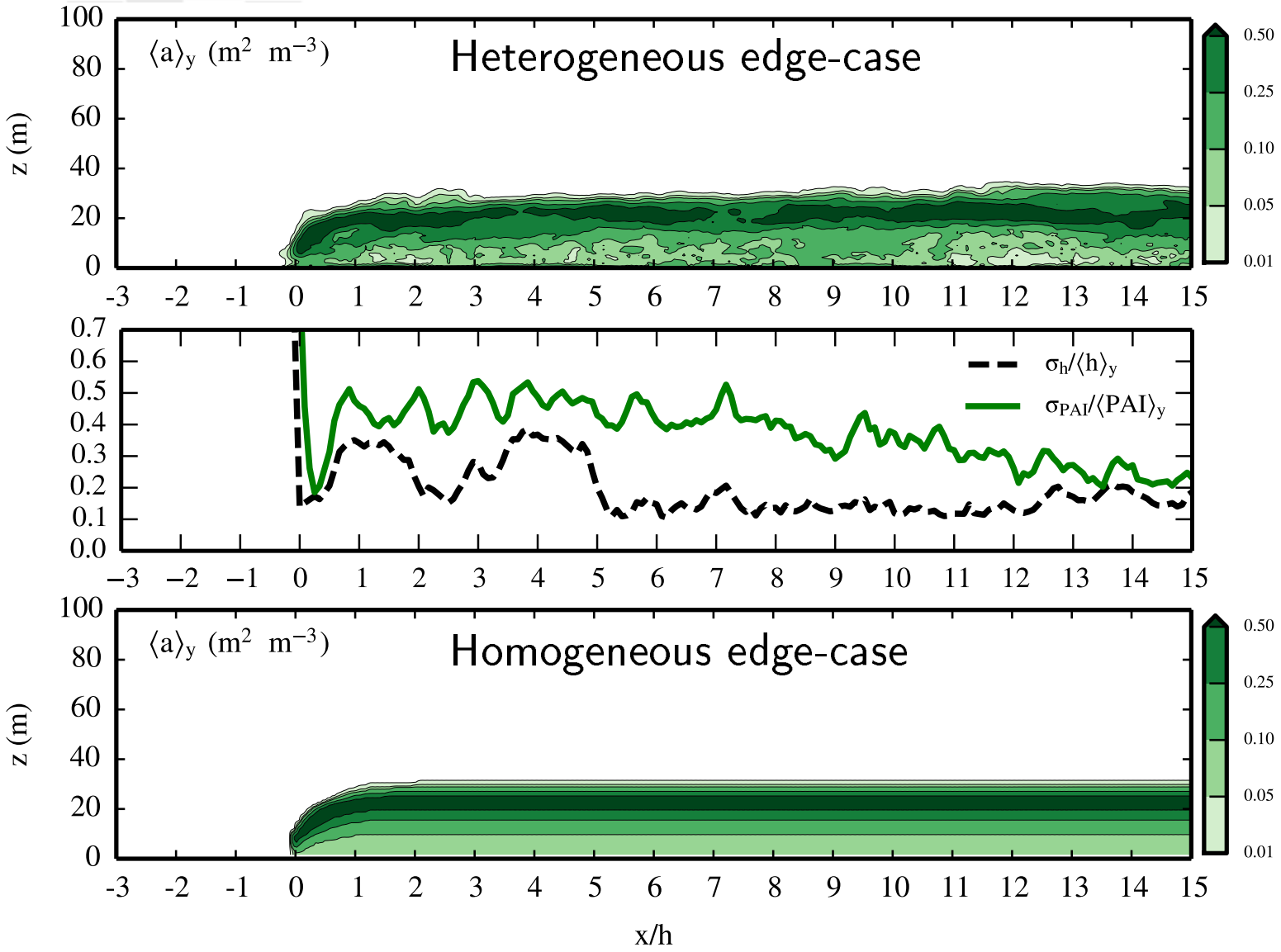
- Spatially-filtered $\widetilde{NS - eqns}$.
- 1.5-order SGS model

  (Deardoff, 1980)
- Modified for canopy flow

  (Dupont & Brunet, 2008, 2009 ; Dupont *et al.*, 2011)
- Solved with ARPS code

  (Xue *et al.*, 1995 ; 2000 ; 2001)

Case description



Flow averaging framework

- Time + spatial averaging :

$$\phi_i' = \phi_i - \bar{\phi}_i$$
$$\bar{\phi}_i'' = \bar{\phi}_i - \langle \bar{\phi}_i \rangle \qquad (\langle \bar{\phi}_i \rangle_y \text{ or } \langle \bar{\phi}_i \rangle_{xy})$$

- Inhomogeneous canopy : dispersive fluxes important ?

$$\frac{\partial \langle \bar{u}_i \rangle}{\partial t} = -\langle \bar{u}_j \rangle \frac{\partial \langle \bar{u}_i \rangle}{\partial x_j} - \frac{1}{\rho} \frac{\partial \langle \bar{p} \rangle}{\partial x_i} - \frac{\partial \langle T_{ij}^{tot} \rangle}{\partial x_j} - \langle F_D^{tot} \rangle$$

Second-order moments :

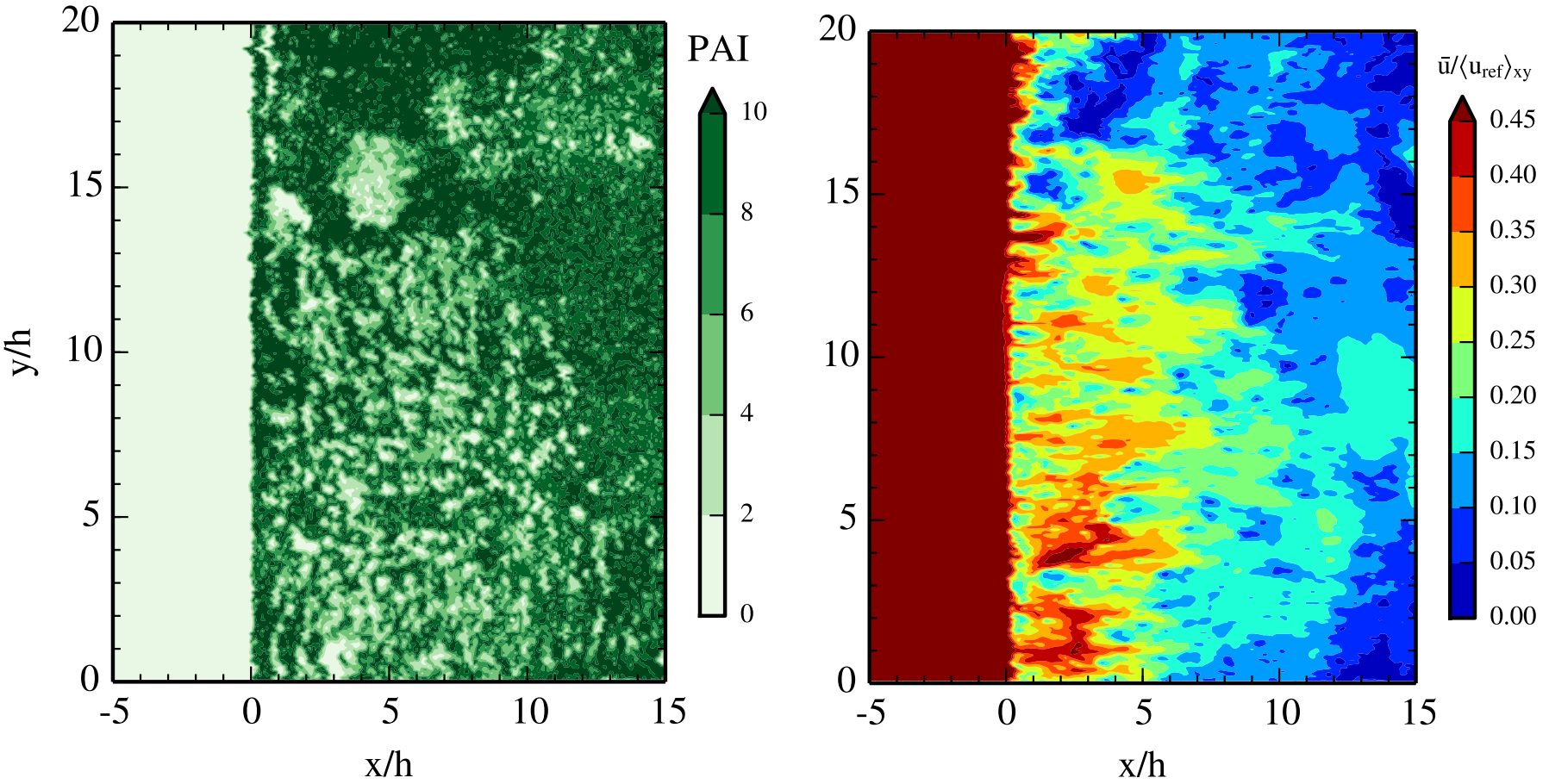
$$\langle T_{ij}^{tot} \rangle = \underbrace{\langle \overline{u_i' u_j'} \rangle}_{turbulent} + \underbrace{\langle \bar{u}_i'' \bar{u}_j'' \rangle}_{dispersive}$$

Third-order moments (skewness) :

$$\langle T_{iii}^{tot} \rangle = \underbrace{\langle \overline{u_i' u_i' u_i'} \rangle}_{turbulent} + \underbrace{3\langle \overline{u_i u_i}'' \bar{u}_i'' \rangle - 6\langle \bar{u}_i \rangle \langle \bar{u}_i'' \bar{u}_i'' \rangle + 2\langle \bar{u}_i'' \bar{u}_i'' \bar{u}_i'' \rangle}_{dispersive}$$

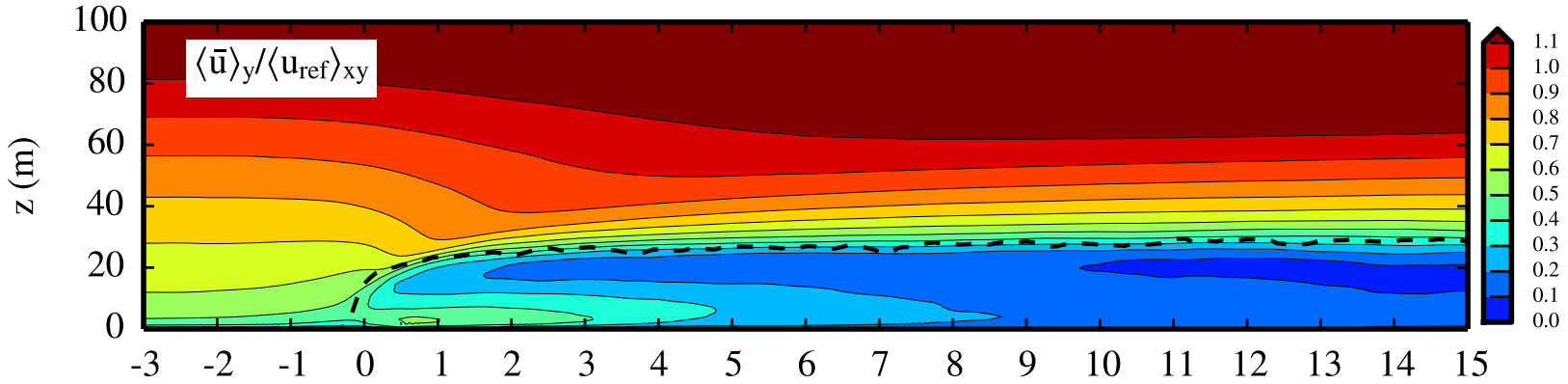
Half-canopy height view

Heterogeneous edge-case

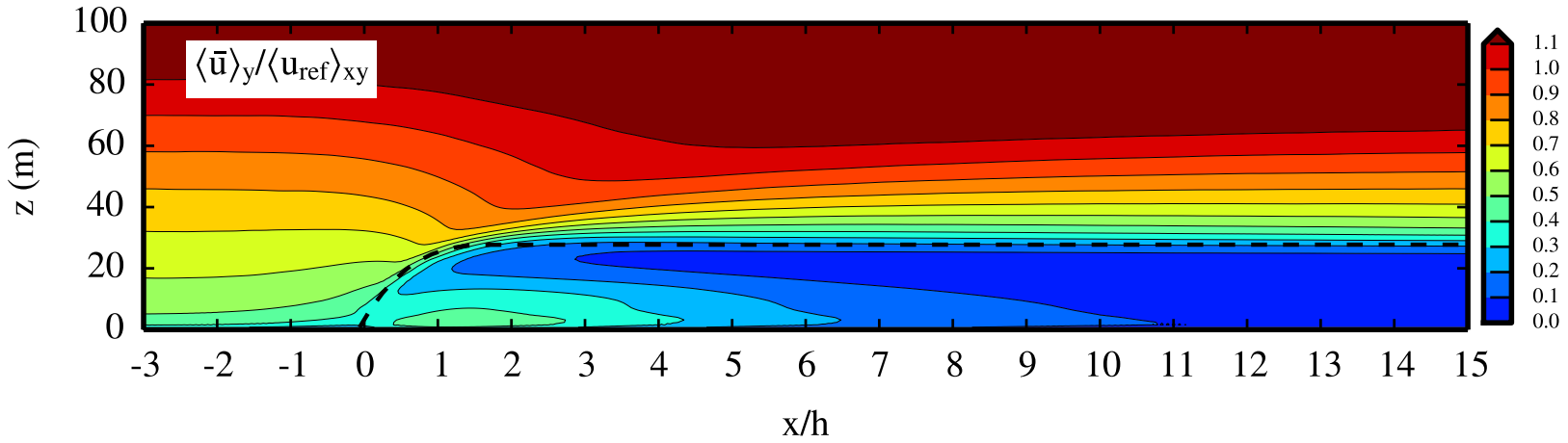


Two-dimensional view : streamwise velocity

Heterogeneous

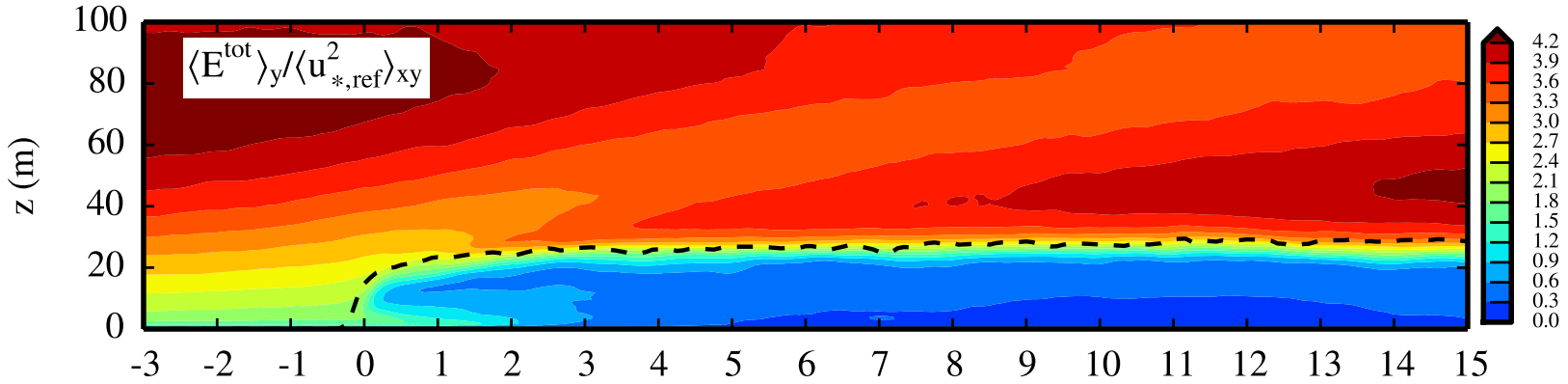


Homogeneous

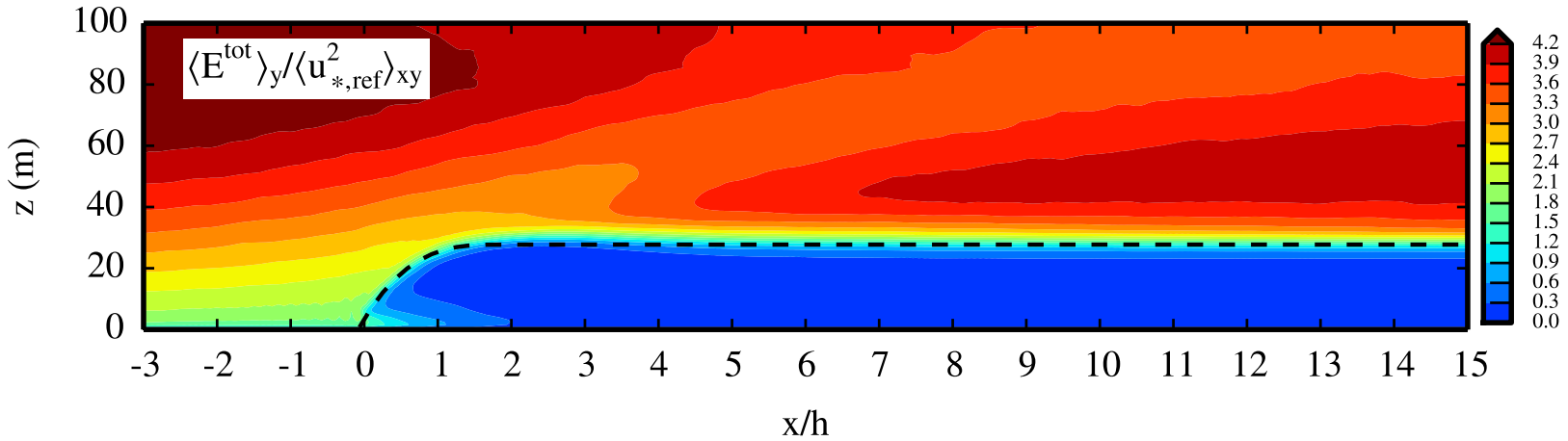


Two-dimensional view : turbulent kinetic energy

Heterogeneous

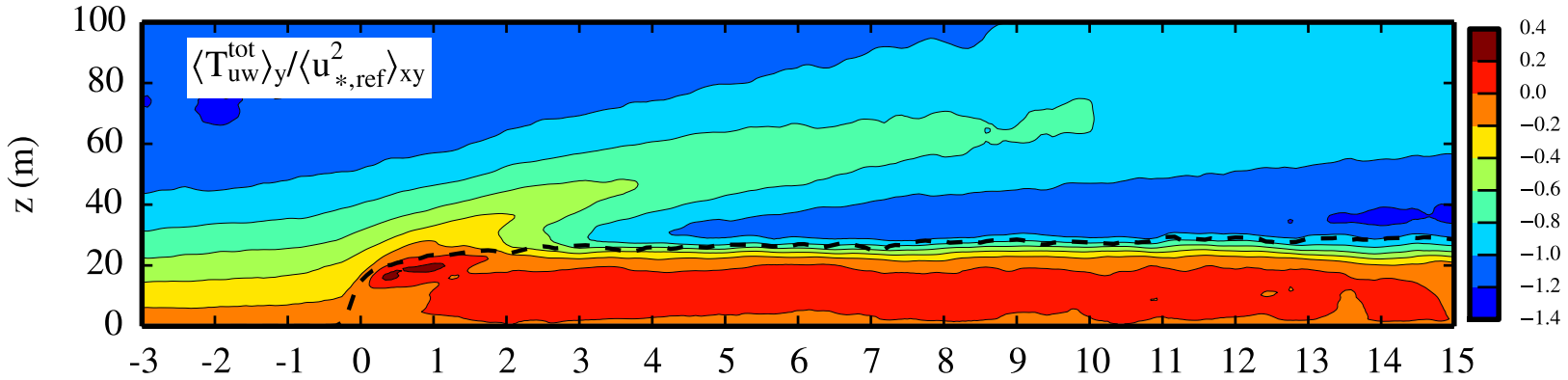


Homogeneous

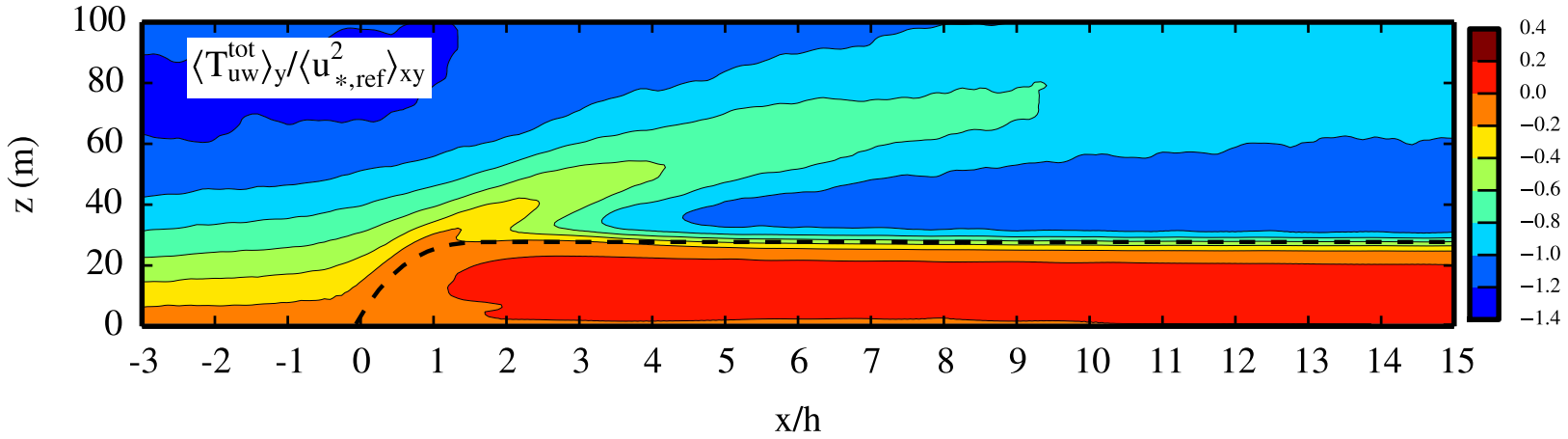


Two-dimensional view : turbulent flux

Heterogeneous

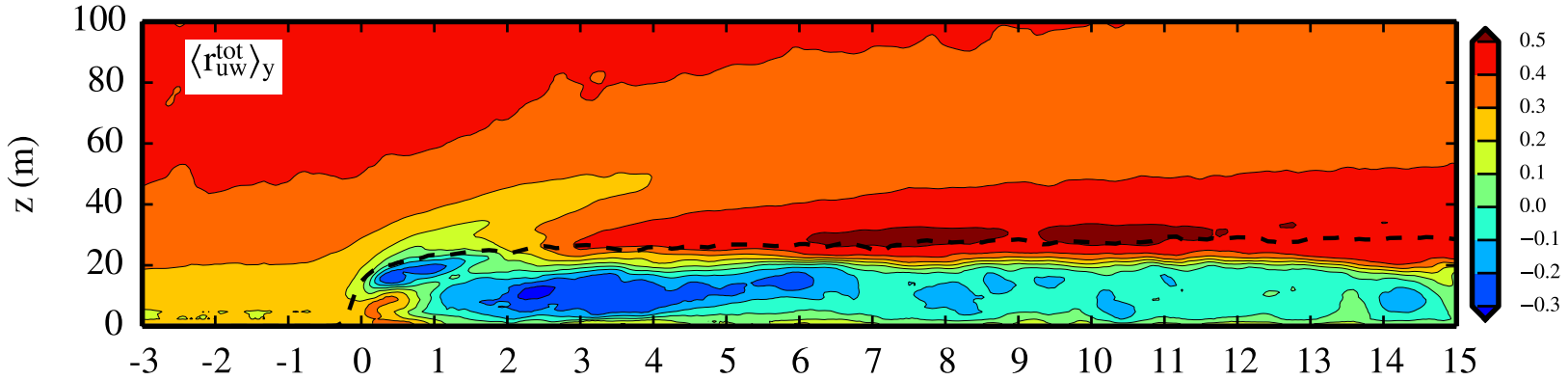


Homogeneous

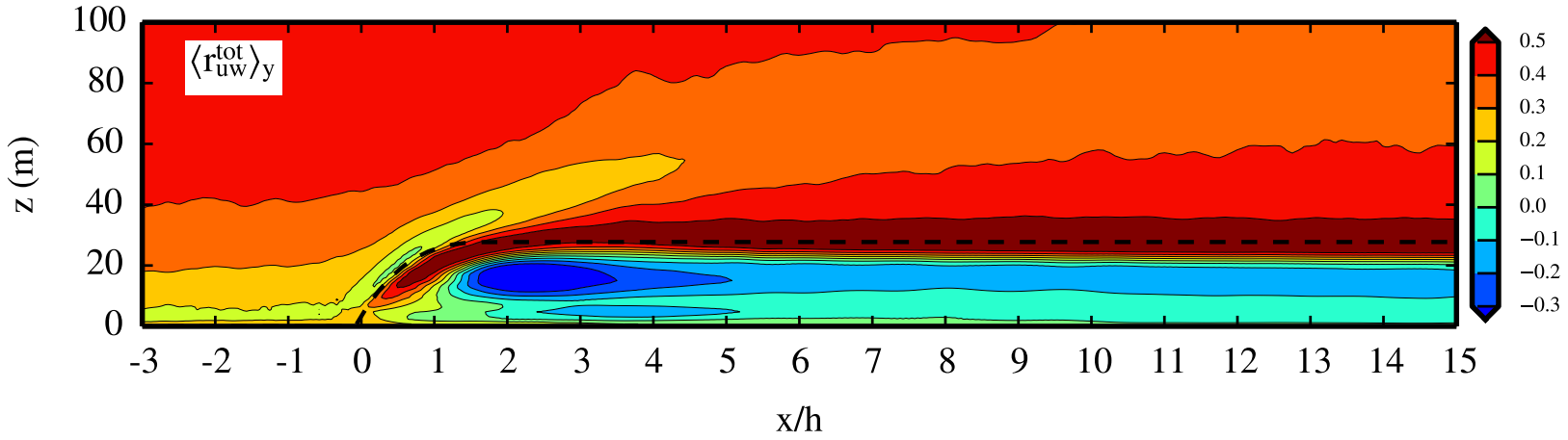


Two-dimensional view : correlation coefficient

Heterogeneous

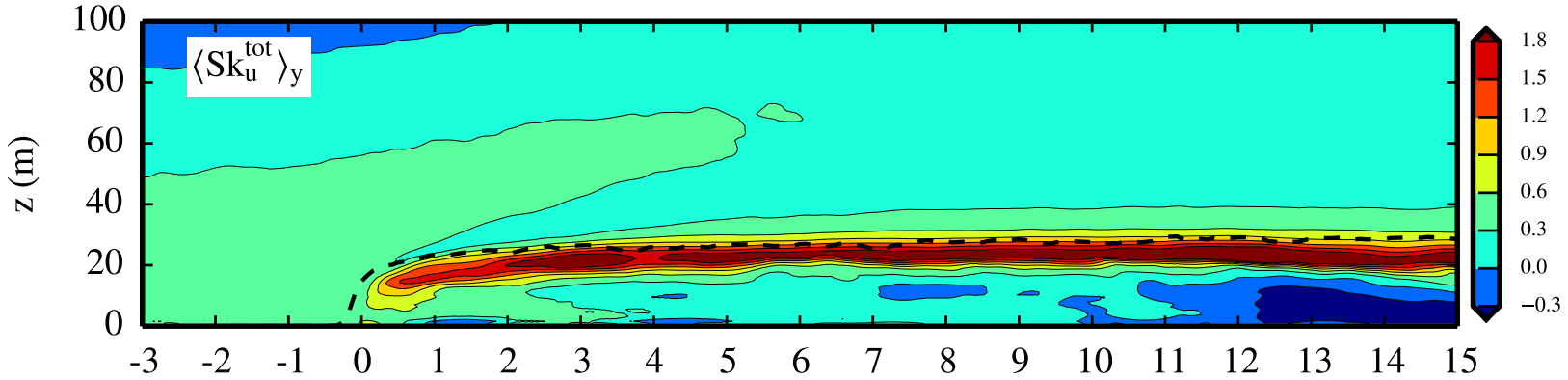


Homogeneous

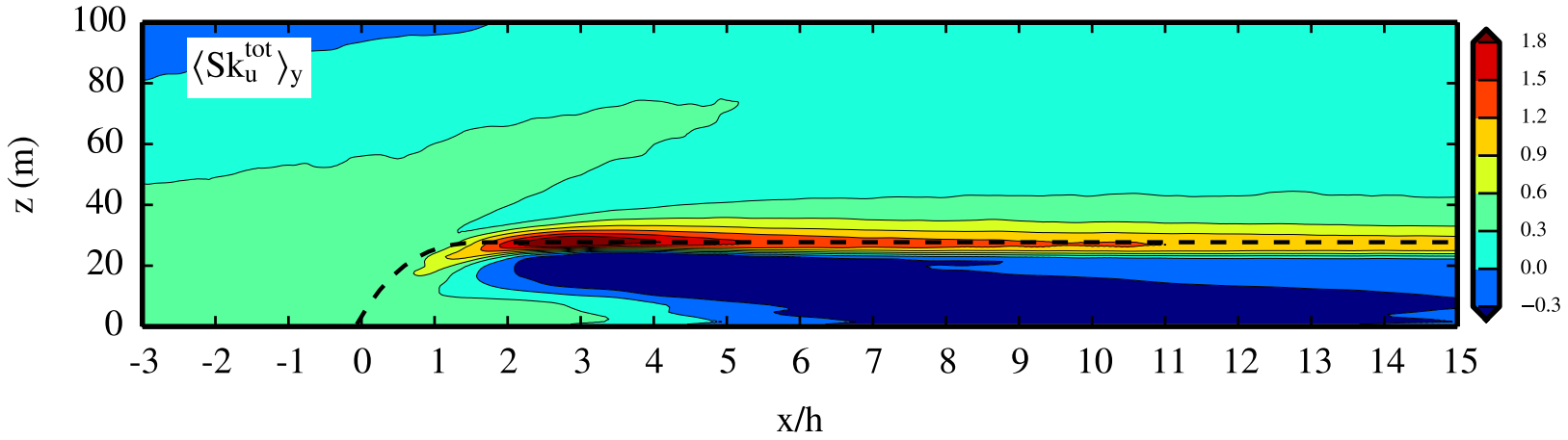


Two-dimensional view : skewness of streamwise velocity

Heterogeneous

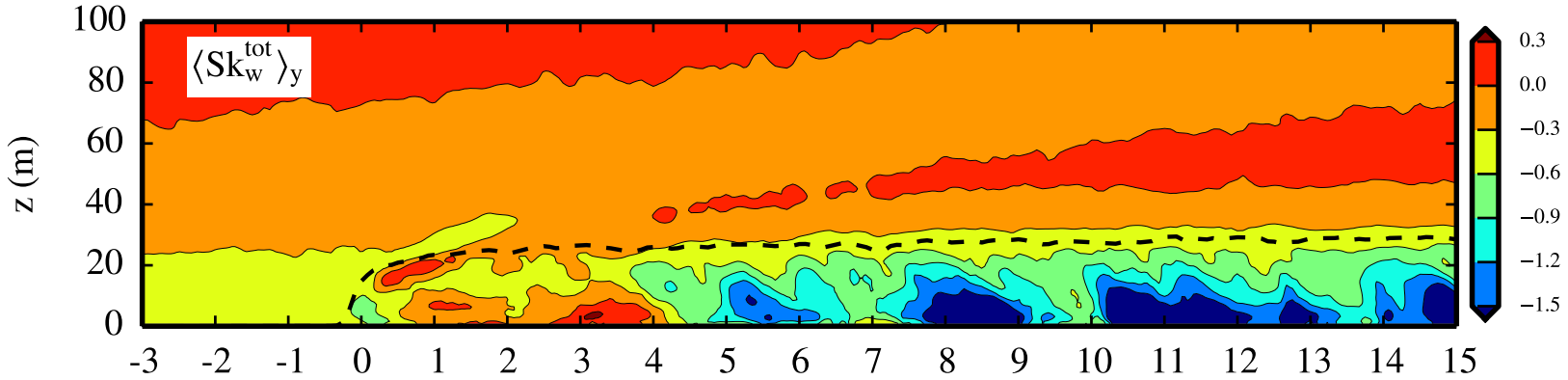


Homogeneous

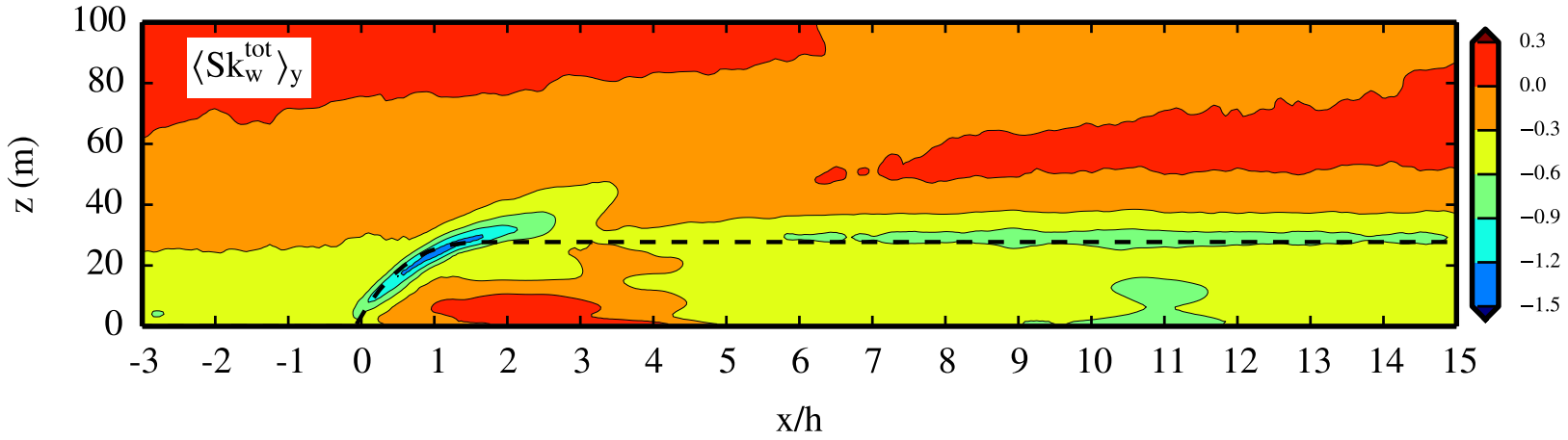


Two-dimensional view : skewness of vertical velocity

Heterogeneous

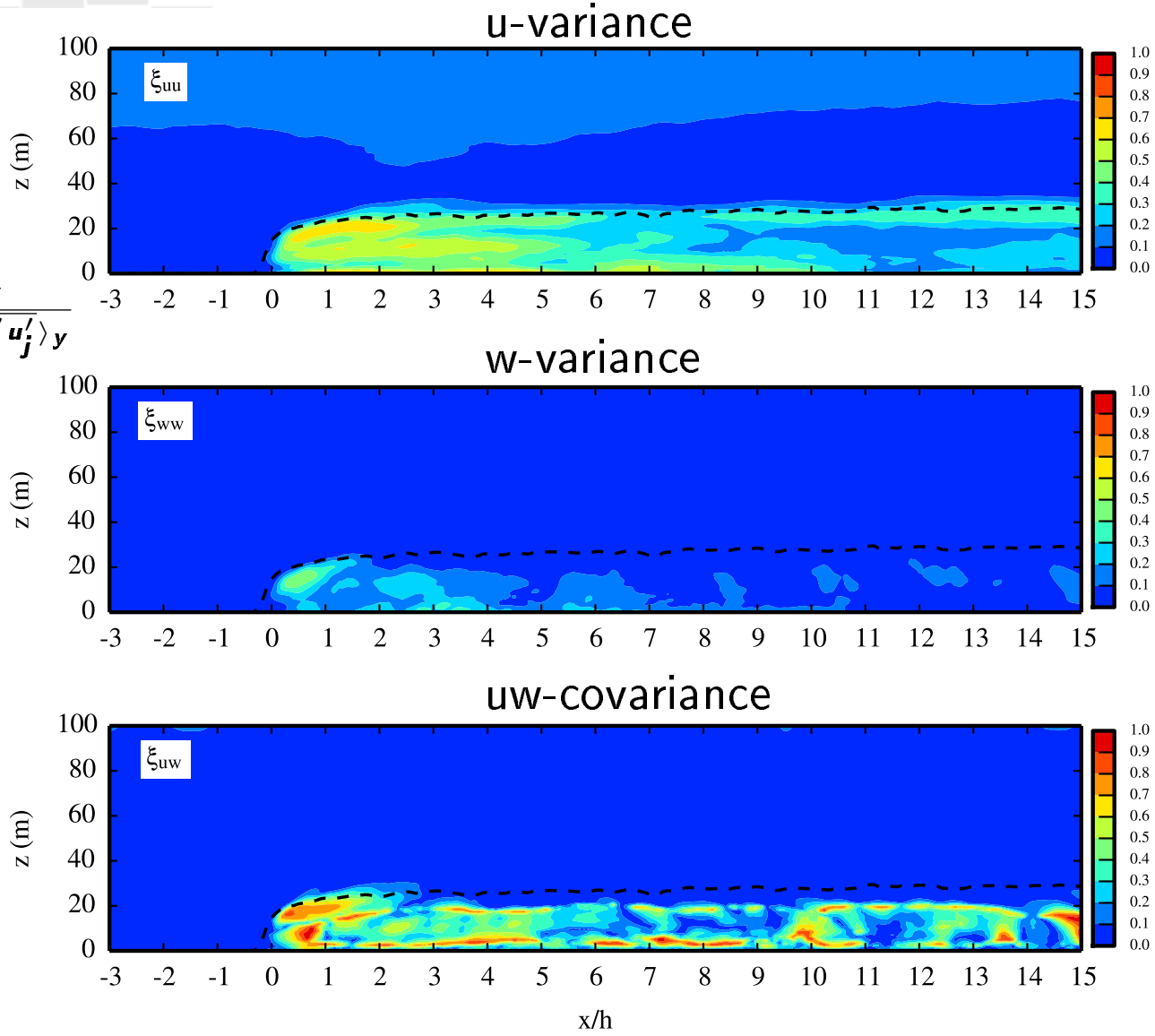


Homogeneous

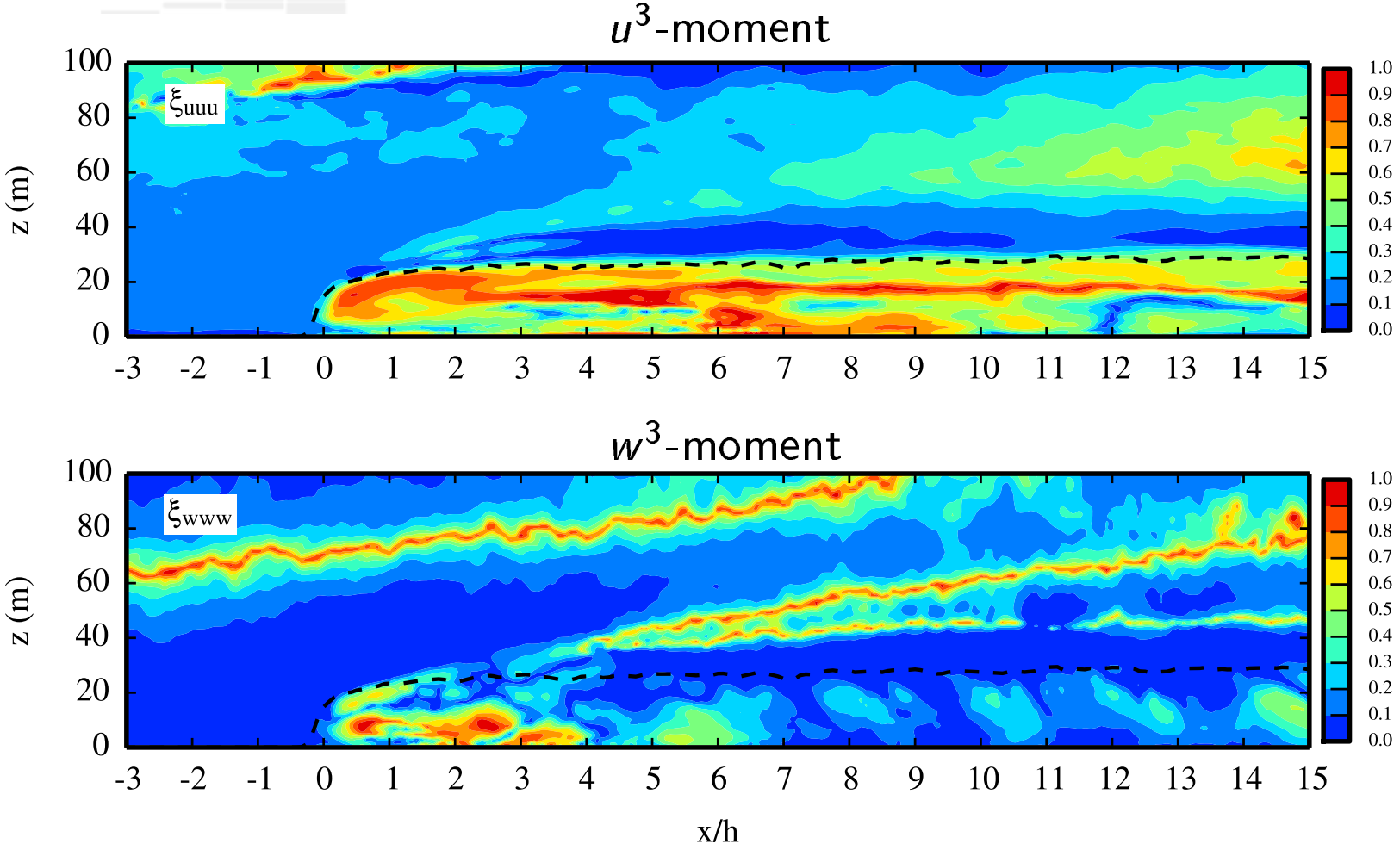


Two-dimensional view : ratio of dispersive to total flux

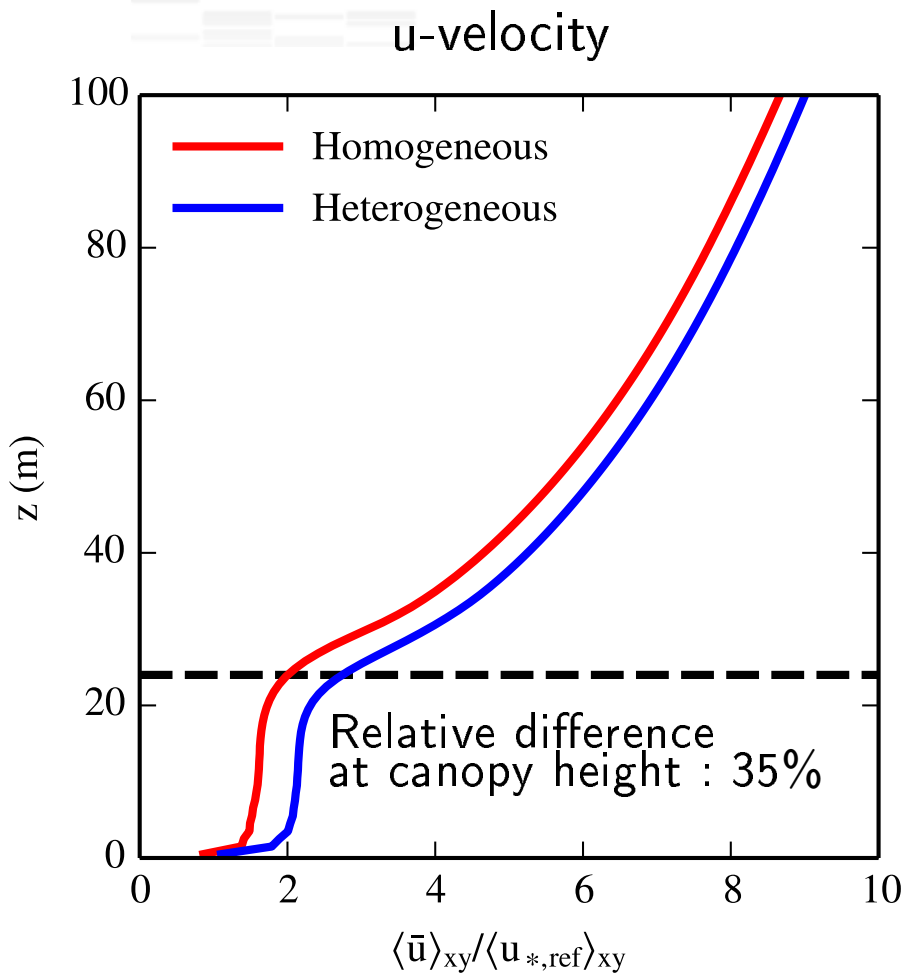
$$\xi_{ij} = \frac{\langle \bar{u}_i'' \bar{u}_j'' \rangle_y}{\langle \bar{u}_i'' \bar{u}_j'' \rangle_y + \langle \overline{u_i' u_j'} \rangle_y}$$

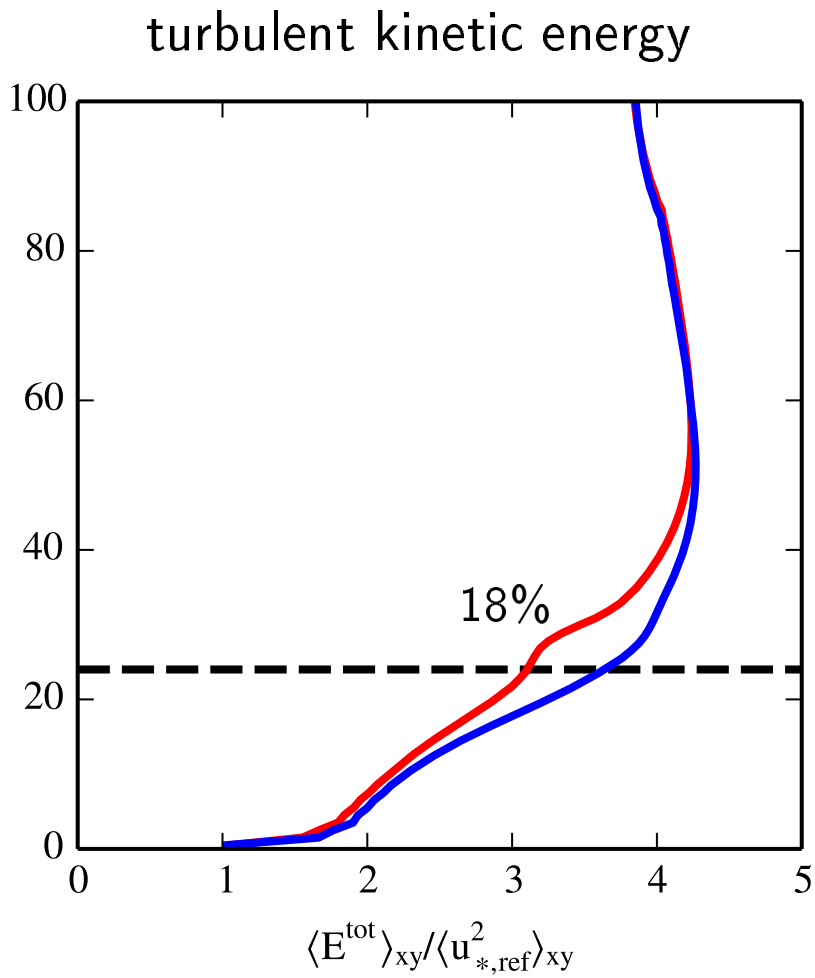


Two-dimensional view : ratio of dispersive to total flux

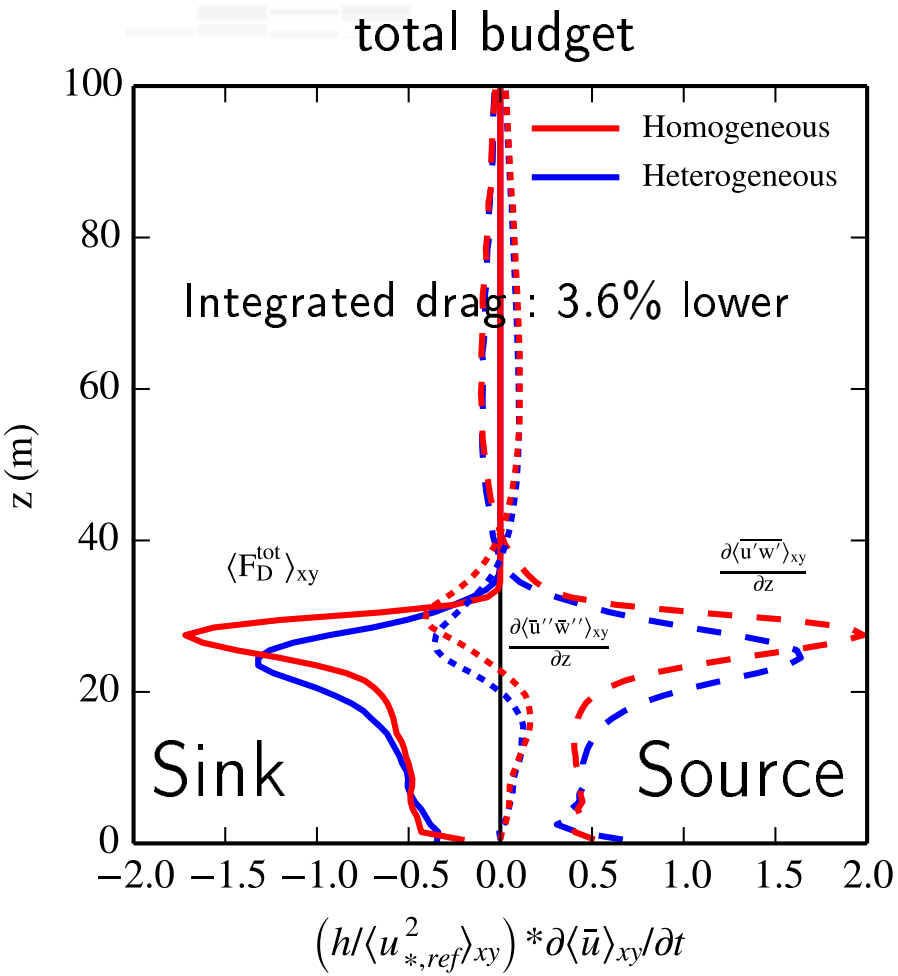


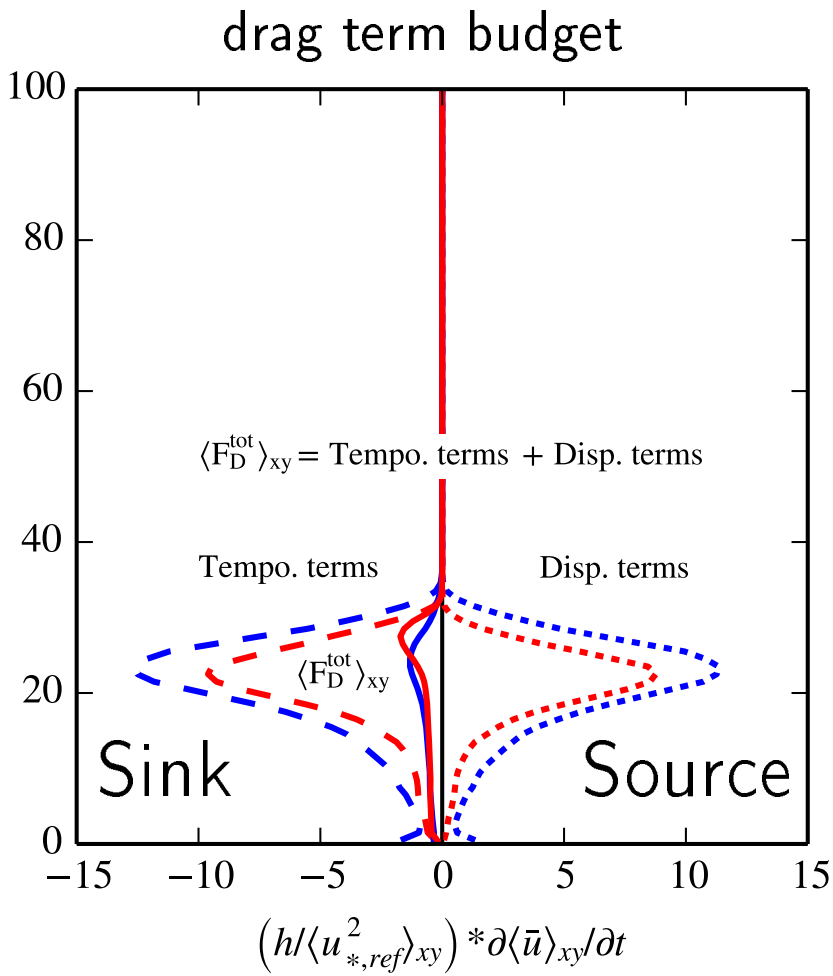
1D u-velocity/TKE





1D u-budget


total budget
Homogeneous
Heterogeneous
Integrated drag : 3.6% lower
$\langle F_D^{tot} \rangle_{xy}$
$\frac{\partial \langle \overline{u'w'} \rangle_{xy}}{\partial z}$
$\frac{\partial \langle \bar{u}''\bar{w}'' \rangle_{xy}}{\partial z}$
Sink
Source
z (m)
100
80
60
40
20
0
−2.0 −1.5 −1.0 −0.5 0.0 0.5 1.0 1.5 2.0
$\left(h/\langle u_{*,ref}^2 \rangle_{xy}\right) * \partial \langle \bar{u} \rangle_{xy}/\partial t$


drag term budget
$\langle F_D^{tot} \rangle_{xy}$ = Tempo. terms + Disp. terms
Tempo. terms
Disp. terms
$\langle F_D^{tot} \rangle_{xy}$
Sink
Source
100
80
60
40
20
0
−15 −10 −5 0 5 10 15
$\left(h/\langle u_{*,ref}^2 \rangle_{xy}\right) * \partial \langle \bar{u} \rangle_{xy}/\partial t$

Conlusion

Impacts of tree-scale heterogeneities in edge flow analysed

Inside the canopy :

1. Faster flow penetration
2. Higher TKE
3. Lower efficiency
4. Higher skewness (gusts)
5. Lower drag
6. Important dispersive fluxes at the edge (10-80% of total flux), up to 50% at canopy top for u-variance

Above the canopy :

1. Slightly higher wind speed / same level of TKE

Consequences :

1. Important to picture well the edge vertical foliage distribution in numerical simulation of homogeneous canopy
2. Underestimation of gust occurence in homogeneous canopy (skewness local)
3. Lower loads on trees / higher production for wind turbines

Thank you for your attention !