LES, lab and empirical representations of a neutral flow over canopy

MAX-PLANCK-INSTITUT FÜR CHEMIE

23-06-2016, Huug Ouwersloot, Arnold Moene, Jisk Attema & Jordi Vilà-Guerau de Arellano

Based on Ouwersloot et al. (Boundary-Layer Meteorology, Accepted)

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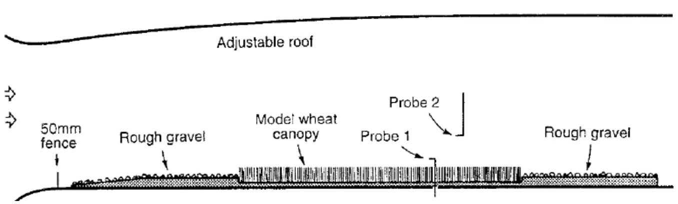
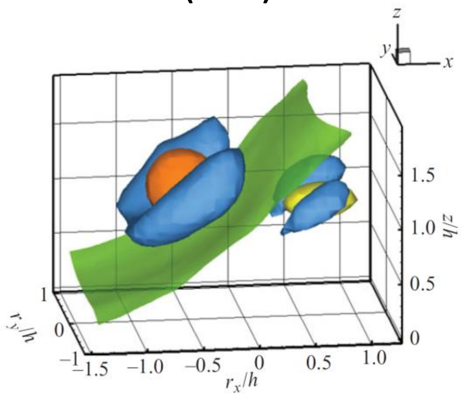
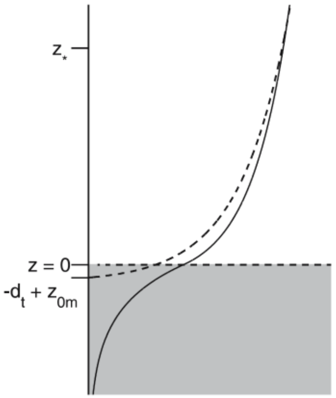
Representations of the flow

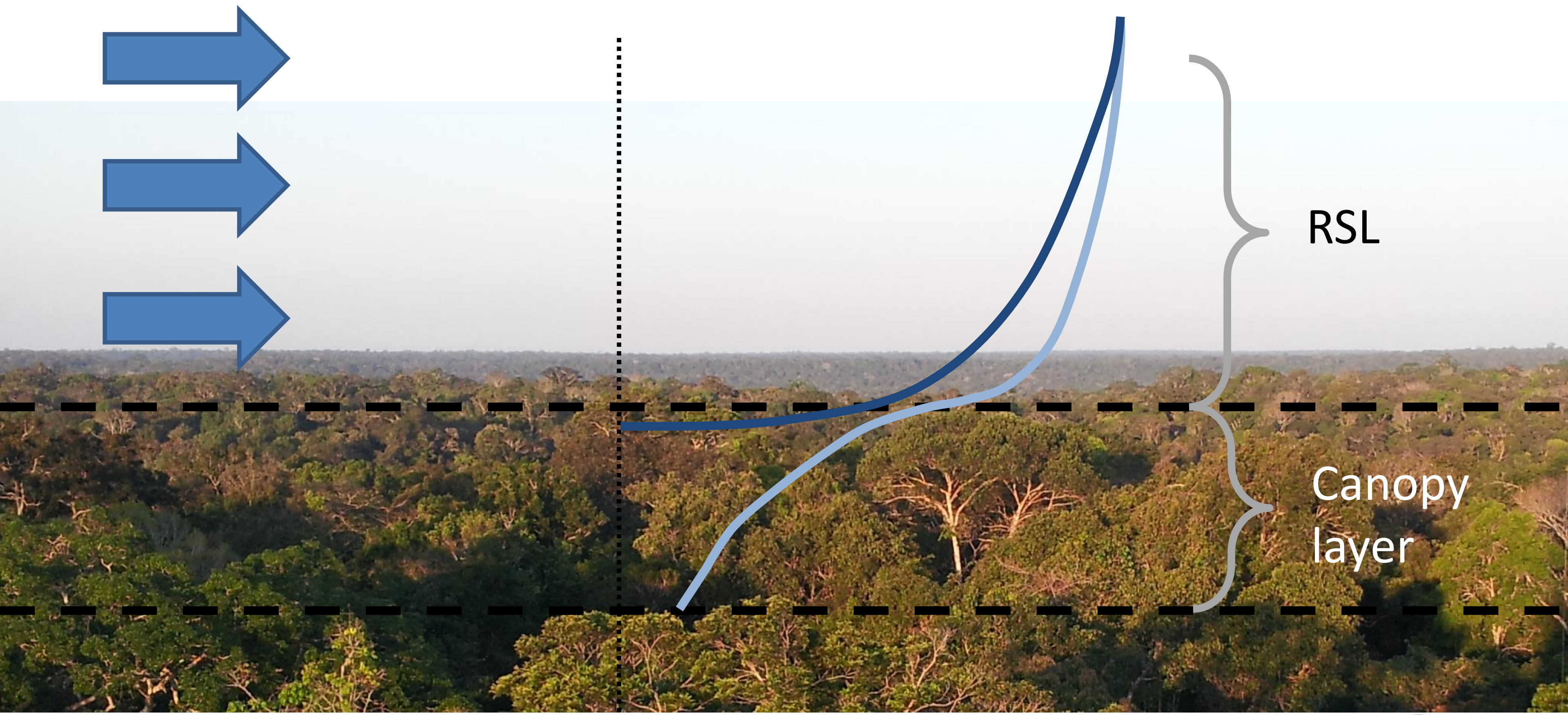
Observations	(Large-Eddy) Simulations (LES)	Empirical relations
		
Brunet et al. (1994, BLM)	Finnigan et al. (2009, JFM)	Harman and Finnigan (2007, BLM)

Combine to **verify** and **interpret**

Research questions

- Are the different methods **consistent**?
  - Can one **representation** be used when evaluating **another**?
- Under what **conditions** do LES **capture** the flow?
  - Canopy density
  - Resolution
- How much of the momentum flux is driven by **organized** structures?
  - Can **mean** properties of **quadrants** be used to measure flux?

Focus on Roughness SubLayer (RSL)



Comparison

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- **Wind-tunnel** data: Brunet et al. (1994, BLM)
- **Emperical** relations: Harman and Finnigan (2007, BLM)
- **LES** models:
  - **NCAR LES**: Based on Finnigan et al. (2009, JFM)
  - **DALES**: Updated to **v4.1**
    - **2D** parallelization
    - Dynamical **canopy** representation

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Case

- **Based** on the wind-tunnel study
- Canopy: 10 m

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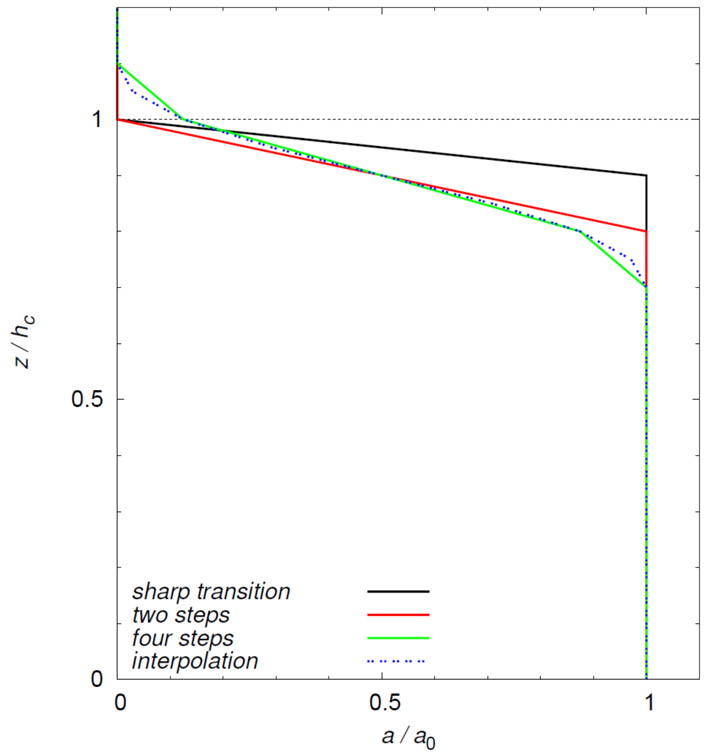


Case

- **Based** on the wind-tunnel study
- Canopy: 10 m
- Pure **neutral** flow
  - θ and q **constant**; no initial perturbations
  - Initial **perturbations** to **velocity** fields
  - **Frictionless rigid** upper lid
  - Height-independent **tendency** to (u,v): vertically **averaged** **(6,0)** m s^{-1}
  - Courant number of 0.63 ($\mathrm{d}t < 0.06$ s at 1 x 1 x 1 m^3 resolution)
  - **Evaluation**: 25 min – 40 min
- Domain: 1024 x 1024 x 128 m^3

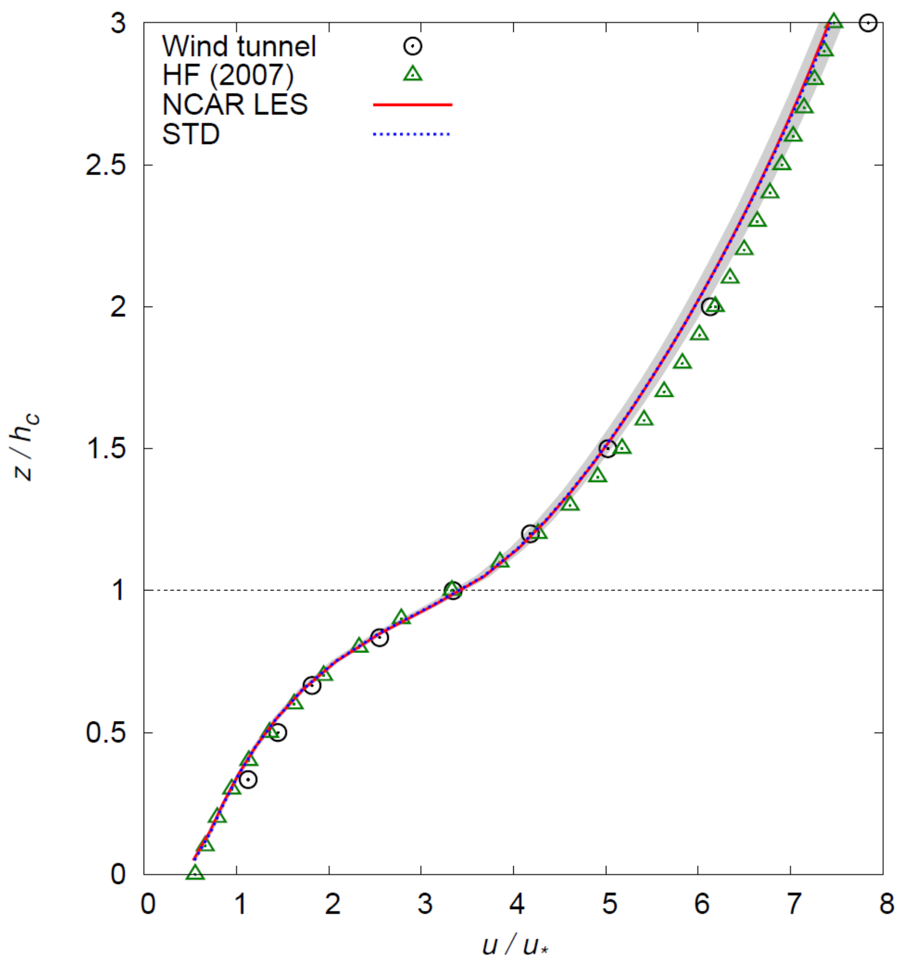
Consistent momentum

Based on LES properties: $\boldsymbol{L_c} \approx 30$ m

$$L_c = \frac{h_c}{C_d\ PAI}$$

Single input to **match** emperical relations with wind-tunnel data and LES experiments

Independent representations yield **similar** profile



HF (2007): Emperical relations STD: Standard DALES experiment

Standard deviations – qualitative match

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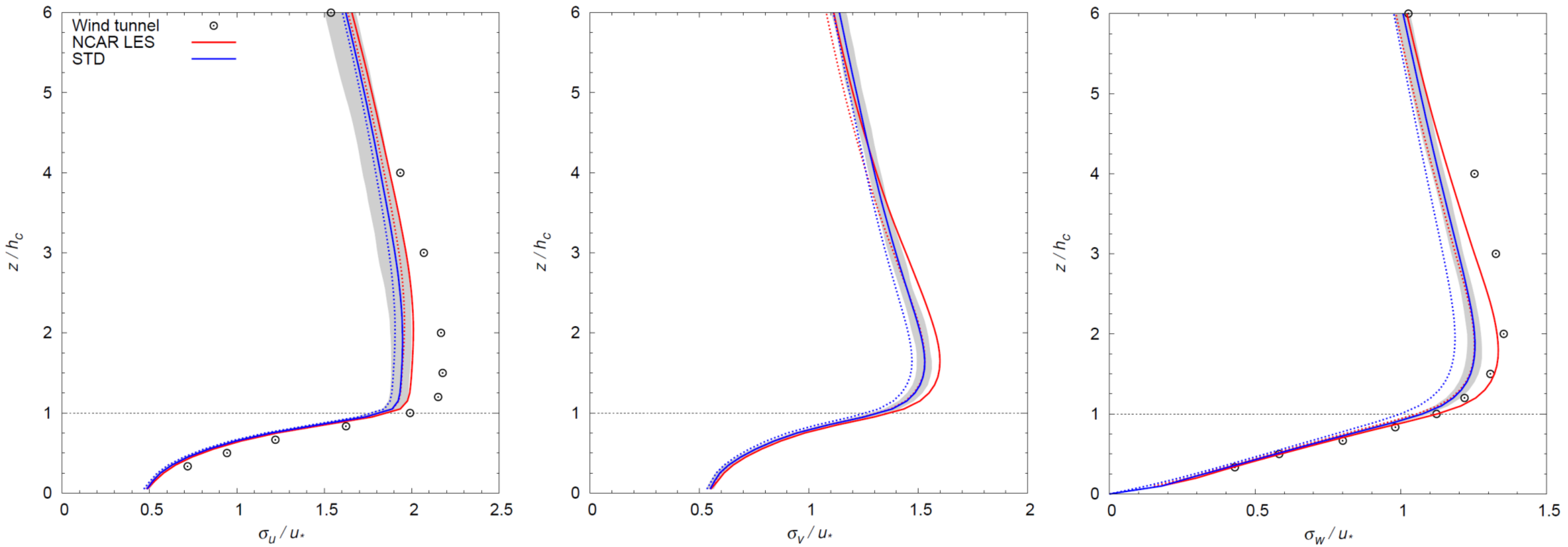

- LES are **comparable**; stronger fluctuations **pseudospectral** NCAR LES
- LES **underestimate** wind-tunnel data: **Generally** the case
  Different **forcing**

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Momentum flux

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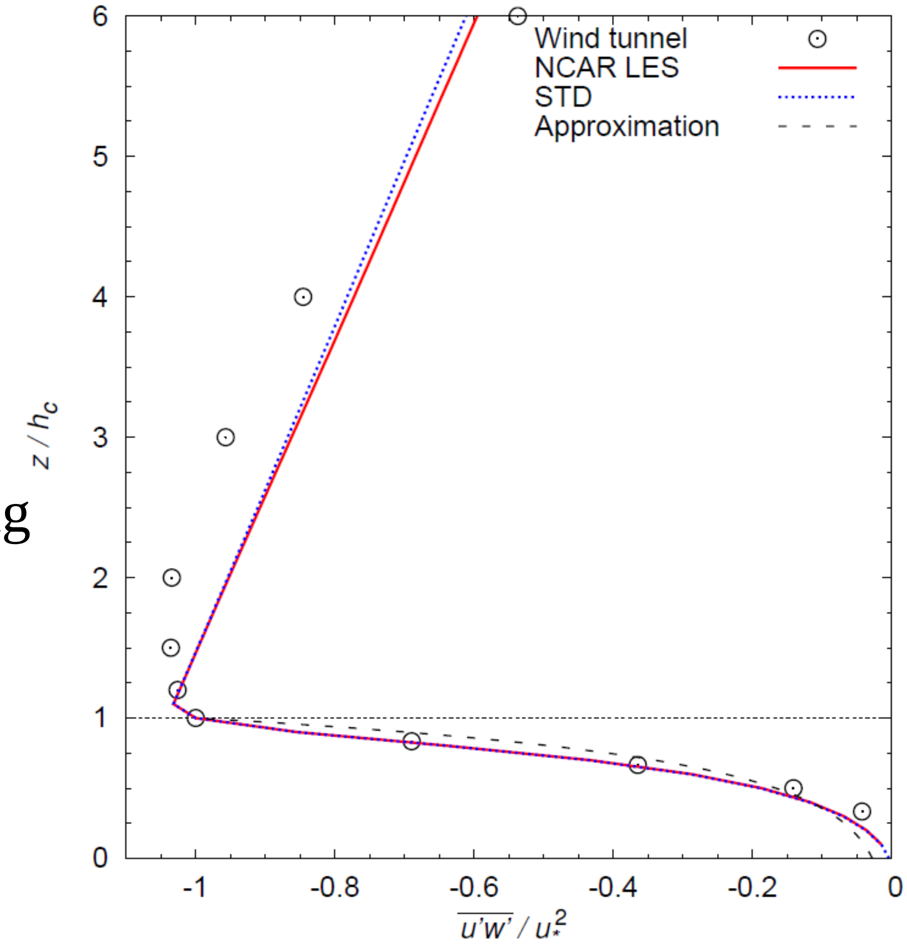
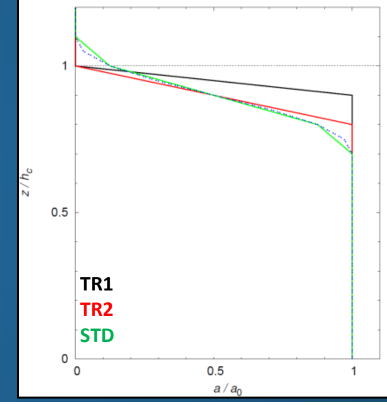
- Different **forcing**
  - Wind tunnel: **freestream** entrainment
  - LES: spatial **invariant** external pressure **gradient**

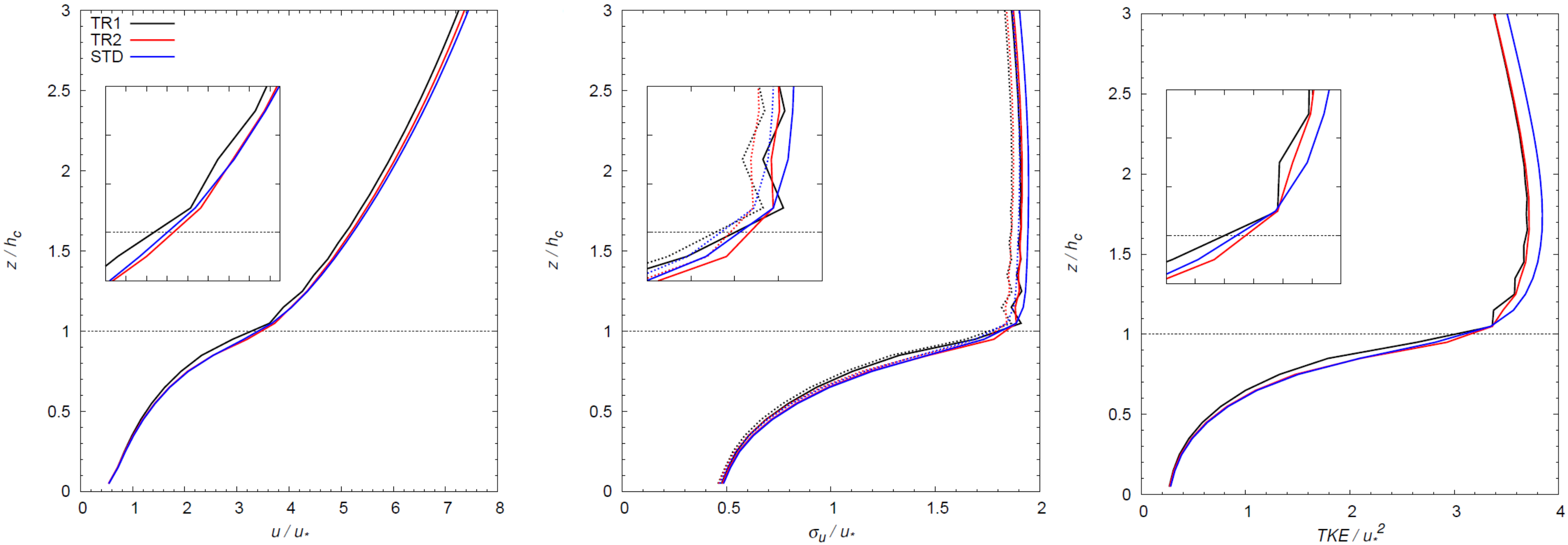
- Can **predict** profile in canopy using **empirical** relations

$$\frac{\overline{u'w'}}{u_*^2} = -\exp\left[\frac{z-h_c}{\beta^2 L_c}\right]$$



Effects of canopy transition





- **Spurious oscillations** are induced by **sharp** transitions at canopy **top**
- Transition **smoothed** over **4** steps to remove all
- **Drawback:** shift in heights of **inflection** and minimum $\overline{u'w'}$

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Resolution dependence

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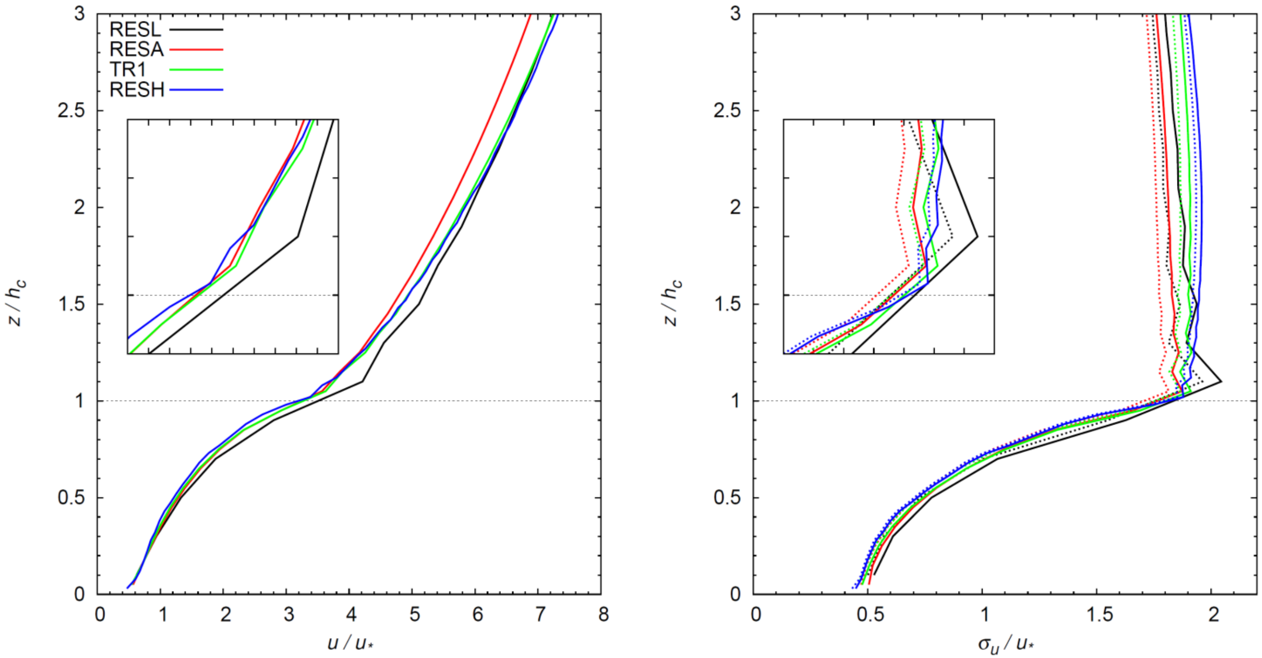
RESL: 2 x 2 x 2 m^3
RESA: 2 x 2 x 1 m^3
TR1: 1 x 1 x 1 m^3
RESH: 0.5 x 0.5 x 0.5 m^3

All with sharp canopy transition

$h_c = 10$ m



– **Isotropic** resolution of **0.1 h_c** suffices to capture flow
– **Anisotropic** grid **not** an **improvement** compared to coarse grid!
– Spurious oscillations' **amplitude** determined by **Δz**

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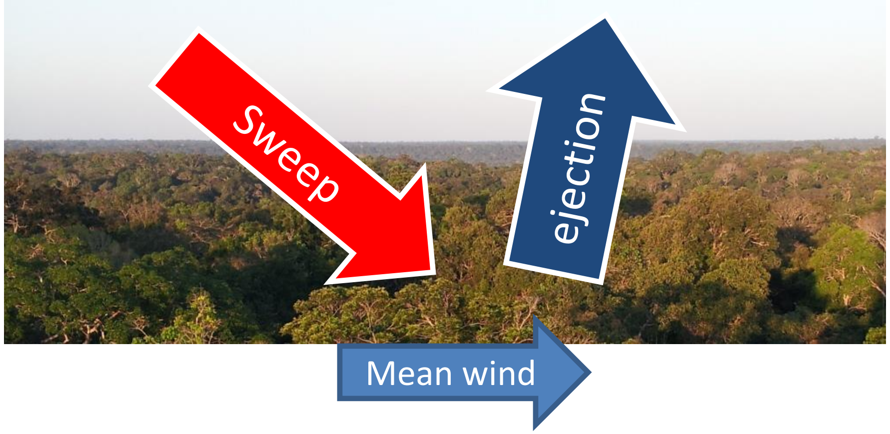
Organized structures: quadrant-hole analysis

- Analyse the nature of **sweeps** and **ejections**



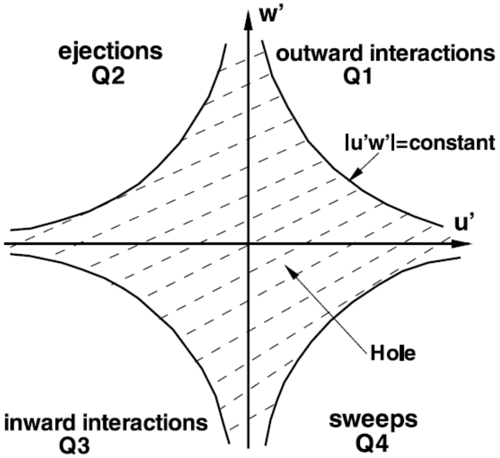


Figure 2. Schematic of quadrant events and "hole" region.

Yue et al., 2007

Organized structures: quadrant-hole analysis

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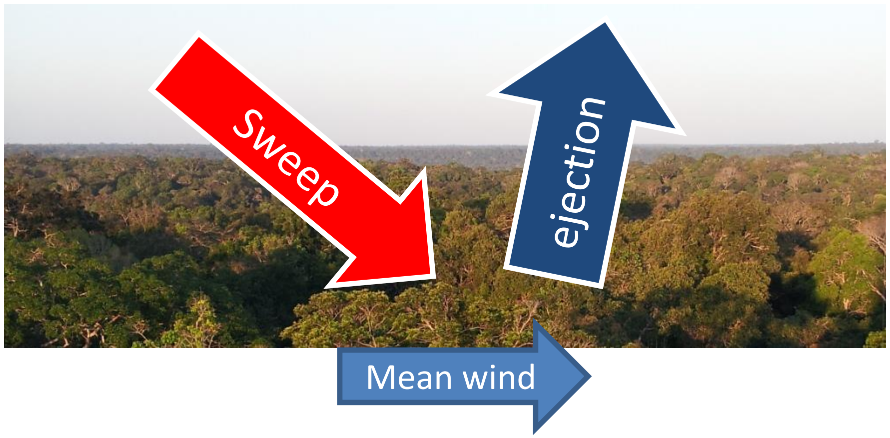

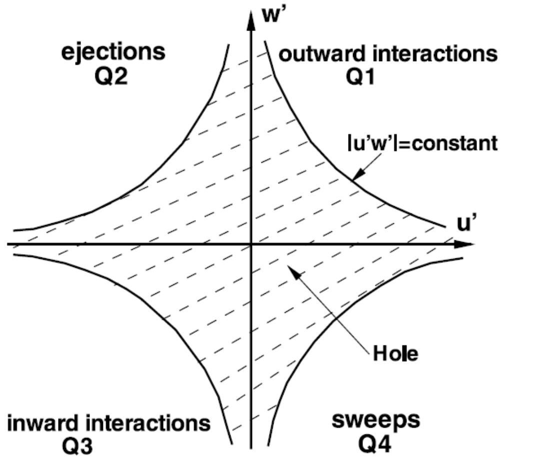

Figure 2. Schematic of quadrant events and "hole" region.

Yue et al., 2007

- Near canopy top: **ejections** most **common**

  sweeps strongest **contribution** to $\overline{u'w'}$

- Results **consistent** with previous studies

Organized structures – momentum transport

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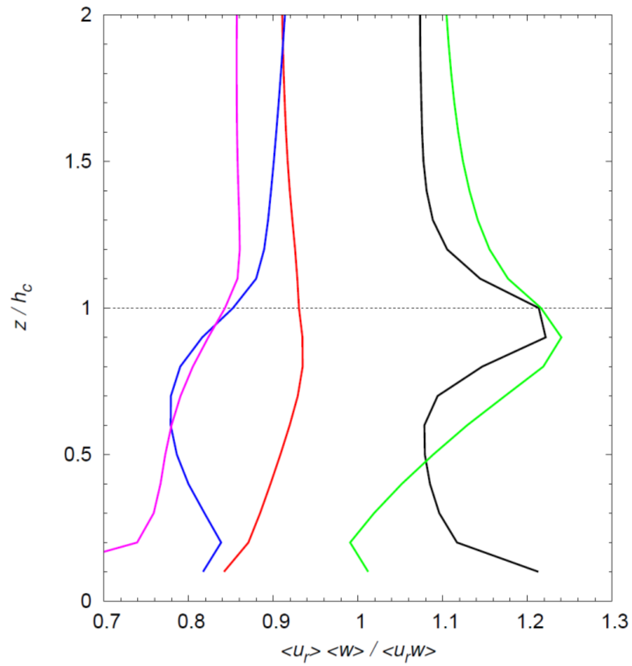
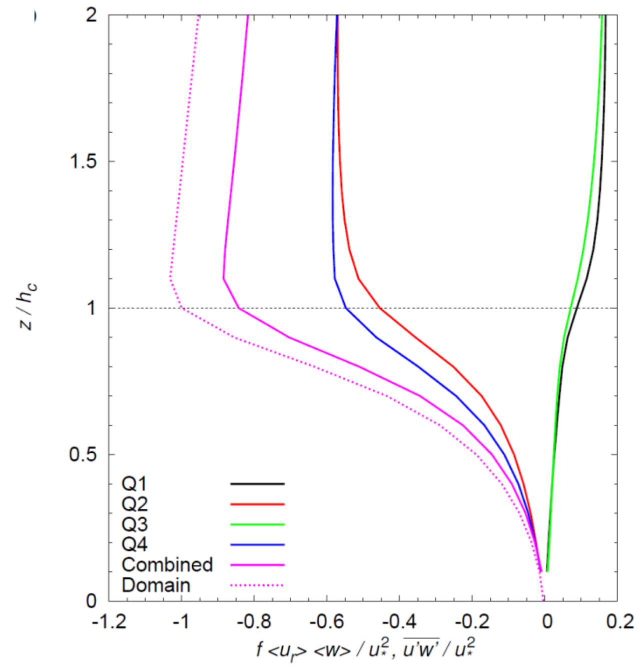
Q1: Outward interactions
Q2: Ejections
Q3: Inward interactions
Q4: Sweeps

Combined:
$\sum_{i=1}^{4} f_i < u_r >_i < w >_i$

f: frequency of occurrence





- **Turbulent** contributions to $< u_r w >$ all **negative**
- **Mean** velocity components in quadrants **dominate** flux
- **Shape** of **combined** mean contributions **resembles** $\overline{u'w'}$

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Mass-flux analogy – using mean values

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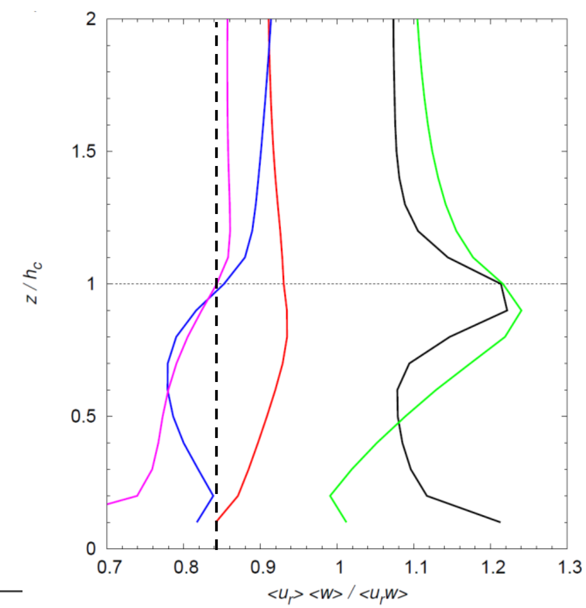
- For convective tranport: $\overline{w'\phi'} \approx a_u(w_u - \overline{w})(\phi_u - \overline{\phi})$

- Relaxed-Eddy Accumulation: $\overline{w'\phi'} \approx \beta\sigma_w(\phi_{up} - \phi_{down})$

- Near canopy top and in RSL:

$$\overline{u'w'} \approx 1.2 \sum_{quadrant} f < u_r >< w >$$



Conclusions

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- **Different** representations shown to be **consistent**
  - One representation useful to **interpret** other's results
  - **DALES** now also **able** to represent canopy
- Spurious **oscillations** can be prevented by **smoothing** transitions over **4** steps
- A **resolution** of $0.1\ h_c \times 0.1\ h_c \times 0.1\ h_c$ suffices
- Momentum **transport** determined by **mean** properties within the **quadrants**

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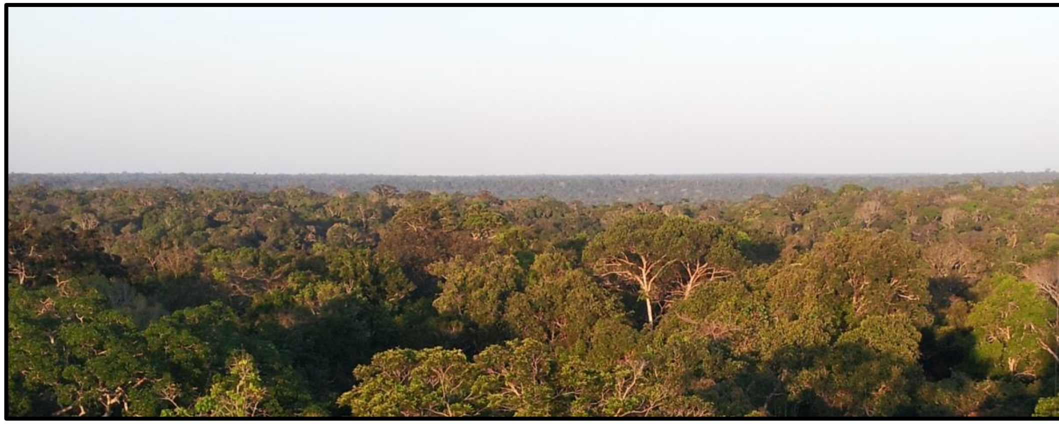
Thank you for your attention

Huug Ouwersloot

Max-Planck-Institut für Chemie
hahn-Meitner-Weg 1
55128 Mainz
http://www.mpic.de



Expected profiles from literature

Dense canopies

In our case:
Penetration depth
$L_c \approx 30$ m

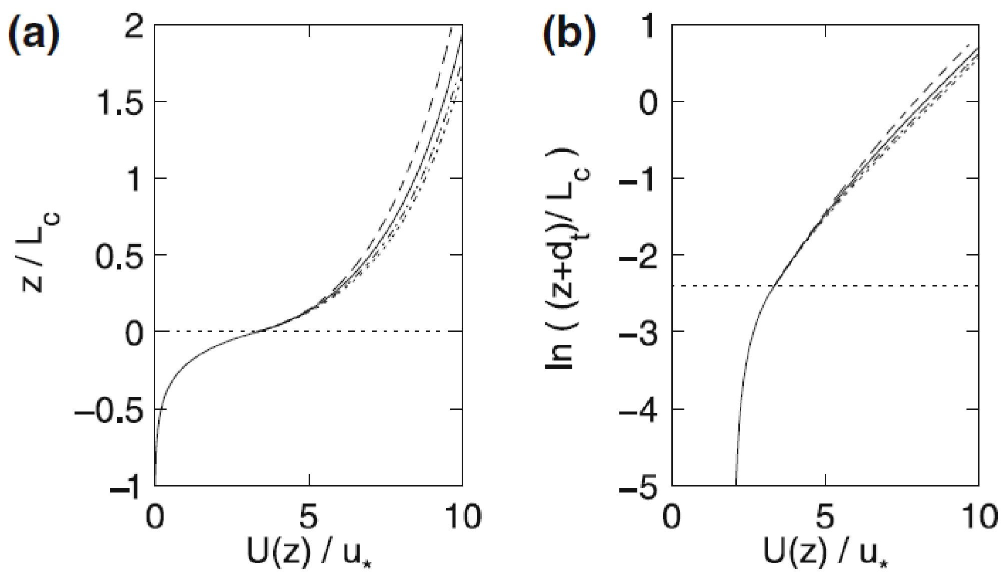
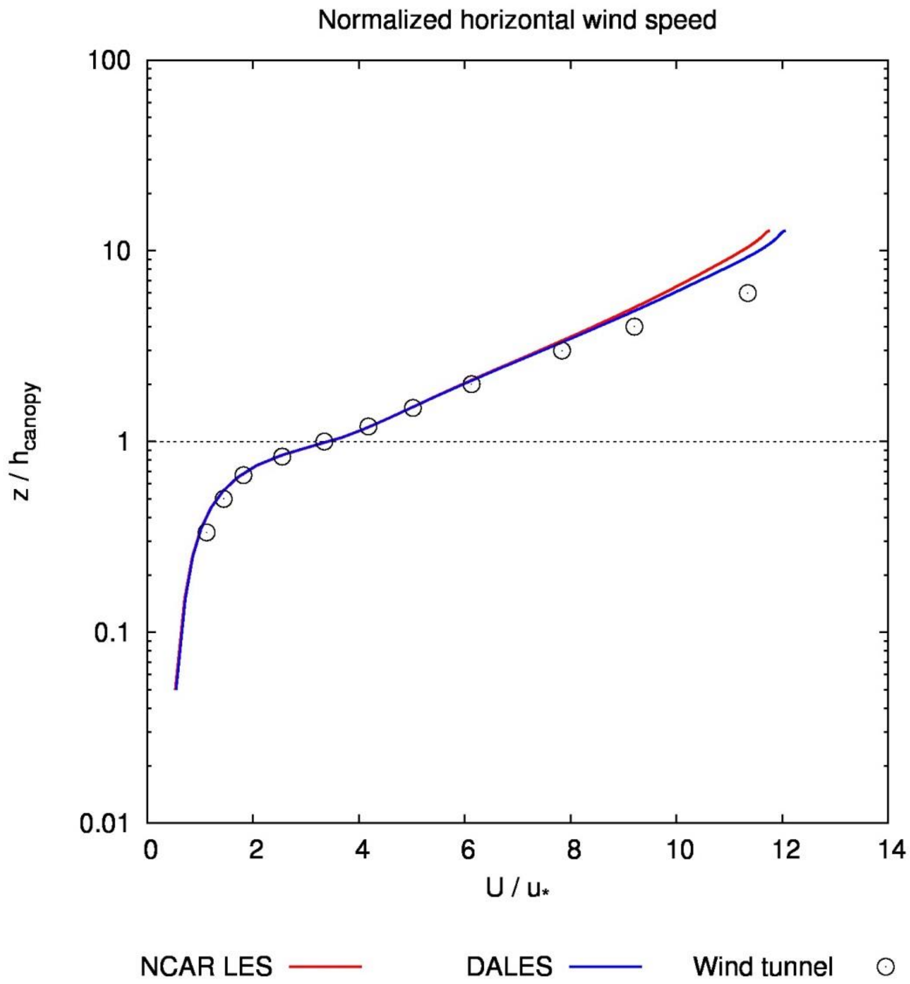


Fig. 3 Sensitivity of the wind speed profile to the value of c_2 in neutral conditions in (**a**) natural and (**b**) log perspectives. Dashed line: $c_2 = 0.25$; solid line: $c_2 = 0.5$; dash-dotted line: $c_2 = 0.75$; dotted line: $c_2 = 1$. Horizontal dotted line indicates the canopy top

Harman and Finnigan (2007)

Backup slides – Log scale plot of U



Influence of wind speed

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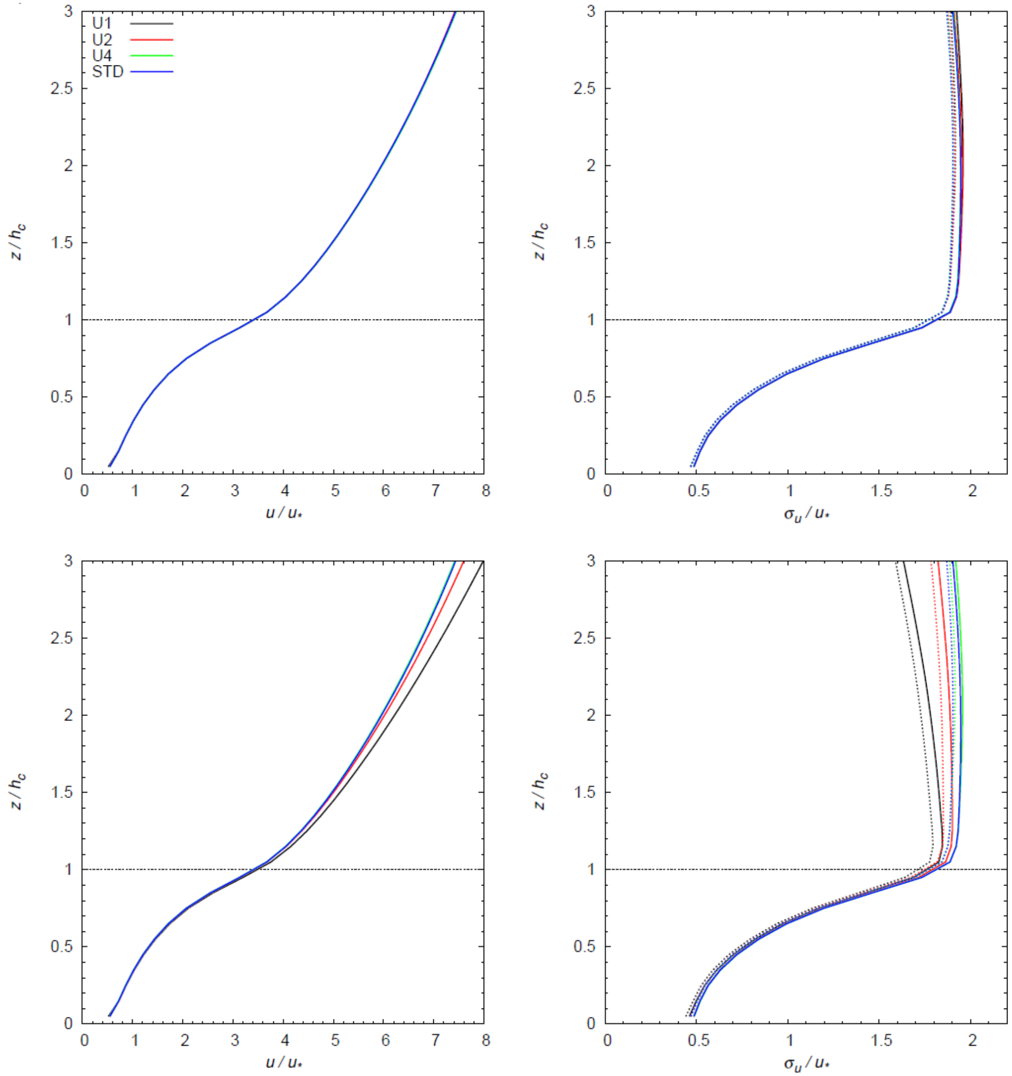

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Q2: ejections
Q4: sweeps

Quadrant analyses

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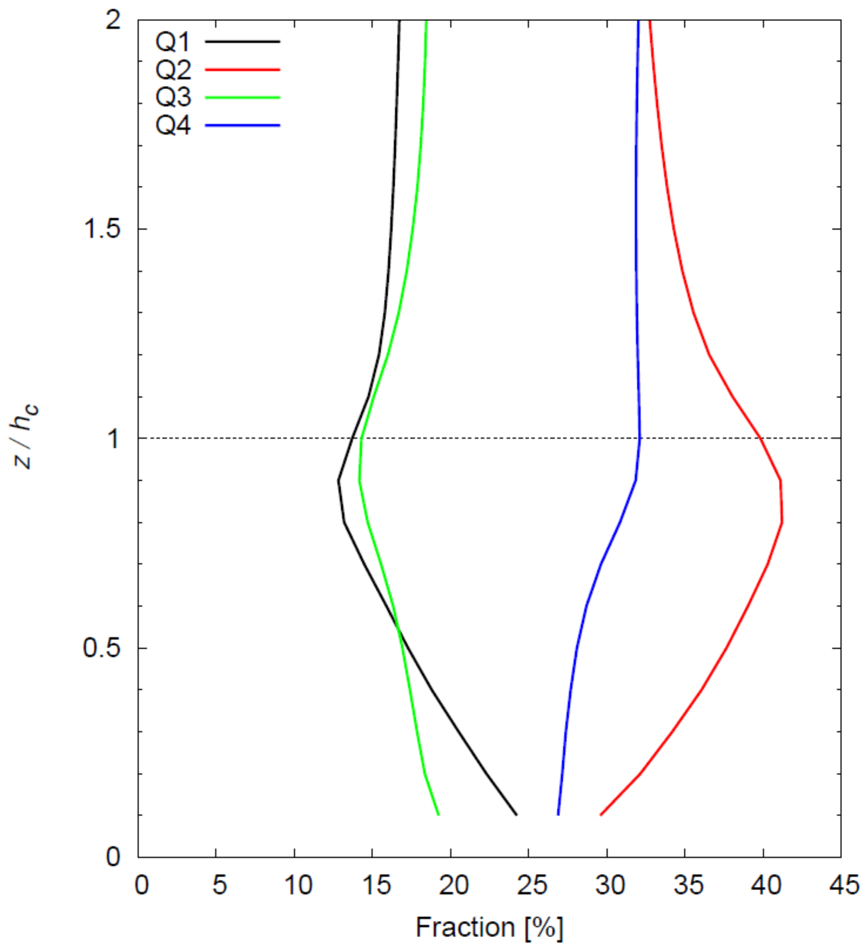

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Quadrant analyses – momentum flux contribution

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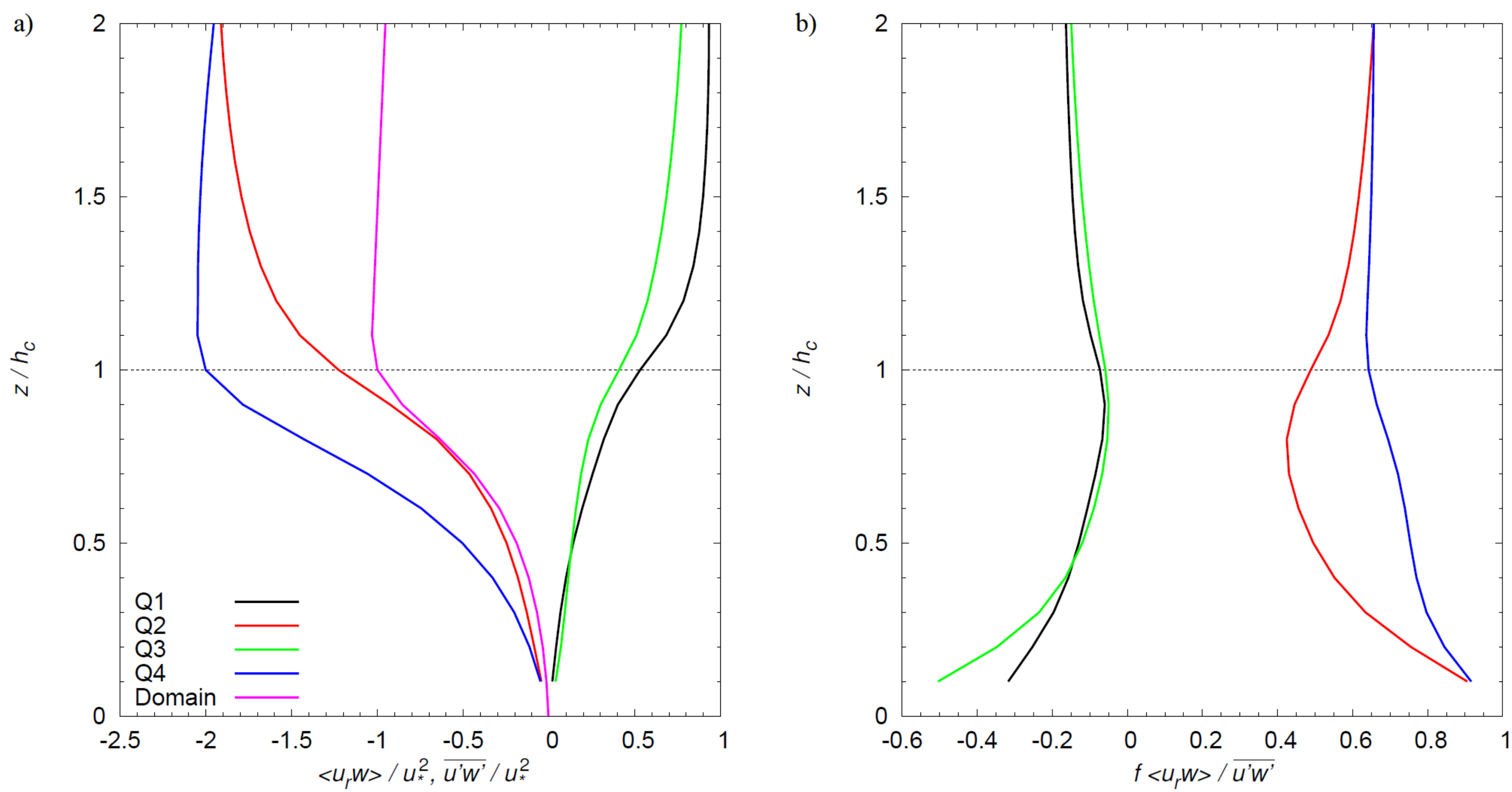

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Canopy

- Prescribed plant area index (**PAI**) [m^2 m^{-2}] and plant area density profile

- **Friction**: $$\left.\frac{\partial u_i}{\partial t}\right|_{canopy} = -c_d \text{ pad } U\, u_i, \text{ with } U = \sqrt{u^2 + v^2 + w^2}$$
$$\left.\frac{\partial \sqrt{e_{sg}}}{\partial t}\right|_{canopy} = -c_d \text{ pad } U \sqrt{e_{sg}}$$

- Prescribed **tendencies** due to flux at the top of the canopy
  - Either including or additional to surface flux
  - Assume exponentially decaying profile

Future developments

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- DALES will be used to **interpret** observations near the canopy top

- To this end we will:
  - Check the canopy code for a **CBL**
  - Implement **interactive** heat flux and evapotranspiration
  - Account for **radiative** transfer in vegetation
  - Expand to include **emissions** depending on atmospheric **conditions**
  - Make use of the new statistical routine for **sweeps** & **ejections**

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