The budget of turbulent kinetic energy within and above a sparse Lodgepole Pine stand

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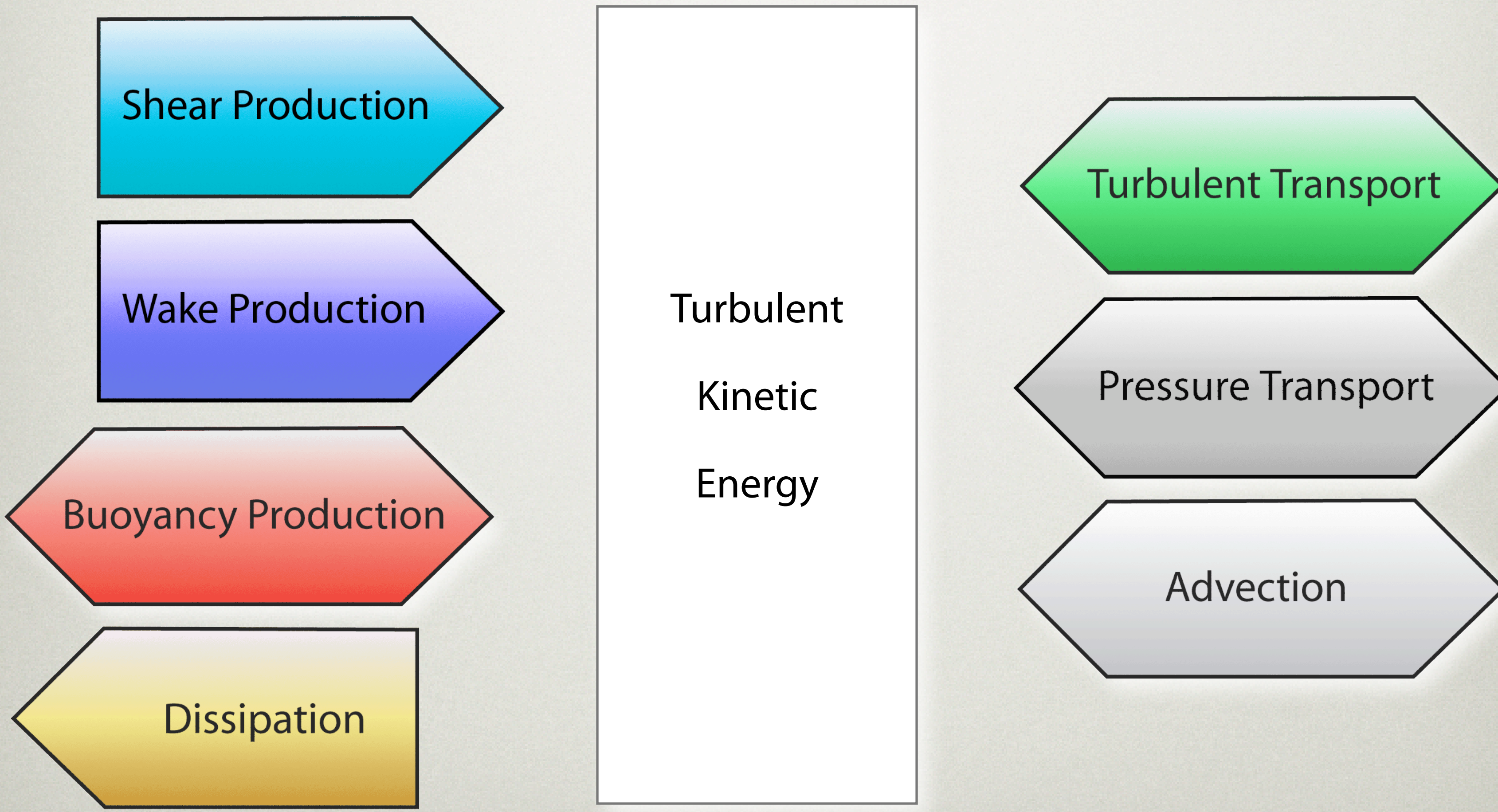
Motivation

- How do changes in stand density and structure control turbulence and turbulent exchange?
- Essential for modelling canopy microclimates. Here: in the context of forest management strategies to combat the Mountain Pine Beetle outbreak in British Columbia.
- Method: Studying the physical processes that create, remove and relocate turbulent kinetic energy (TKE) in stands of different structure.
- Interestingly, most full-scale studies of the TKE budget focussed on dense canopies. Less information is available for sparse canopies.

The budget of turbulent kinetic energy (TKE)



Previous studies

- Meyers and Baldocchi (1991) conclude for a dense forest (LAI ~ 5) that 'below $z/h = 0.75$, the magnitudes of the various components [of the TKE budget] are small compared to their values near the top of the canopy'.
- Lesnik (1974) highlighted the role of turbulent transport of TKE as a significant sink at canopy top and a source in the canopy itself.
- Dwyer et al. (1997) concluded in their LES study of a sparse canopy that pressure transport is important: It is a source well above the forest, a sink at canopy top and an important source in the trunk space.

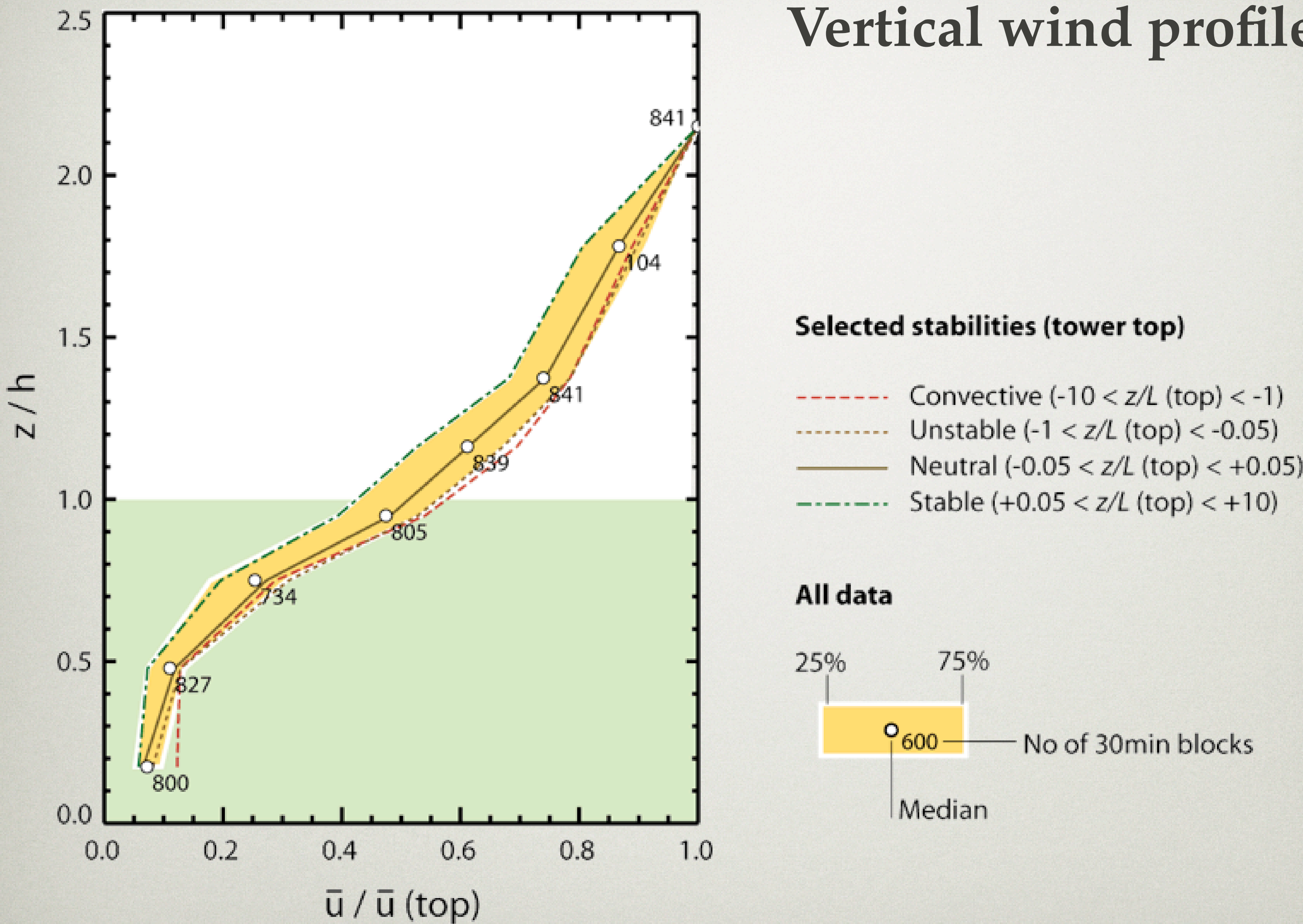
Site

- 'Kennedy Siding', 60 km South of MacKenzie, interior British Columbia, Canada.
- 83 year old canopy with h = 16 m, 1551 stems ha^{-1} and open trunk space.
- Low canopy cover of only 24.3% and cumulative LAI of 1.38.
- Flat terrain, with fetch of at least 1 km in all directions.

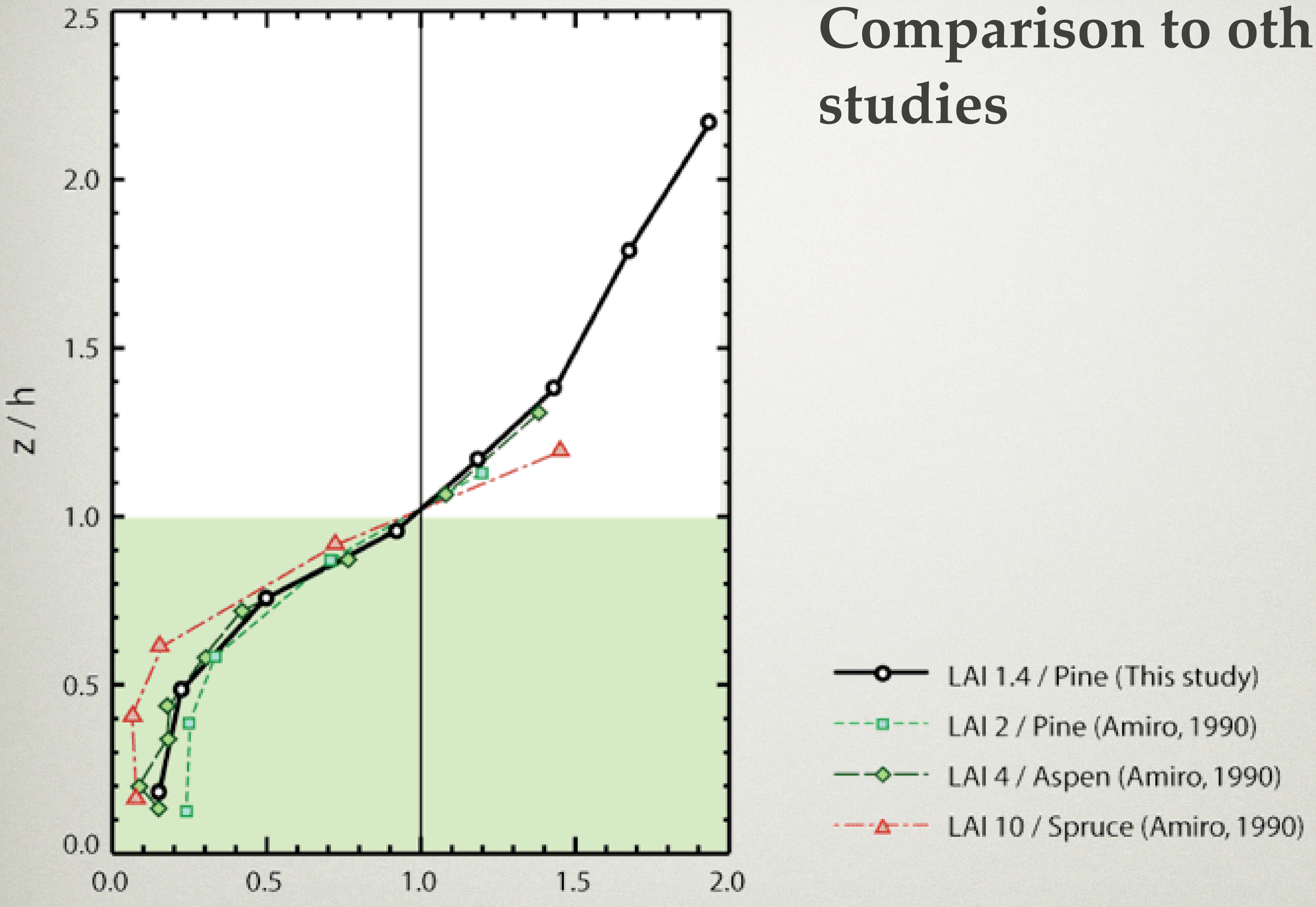
Experiment

- Vertical profile of eight simultaneously operated ultrasonic anemometers-thermometers (Campbell Scientific CSAT-3) and fine-wire thermocouples.
- Four weeks of measurements between Aug 22 and Sep 17, 2007.
- 30-min block averages based on 10 Hz measurements with 1 global rotation.

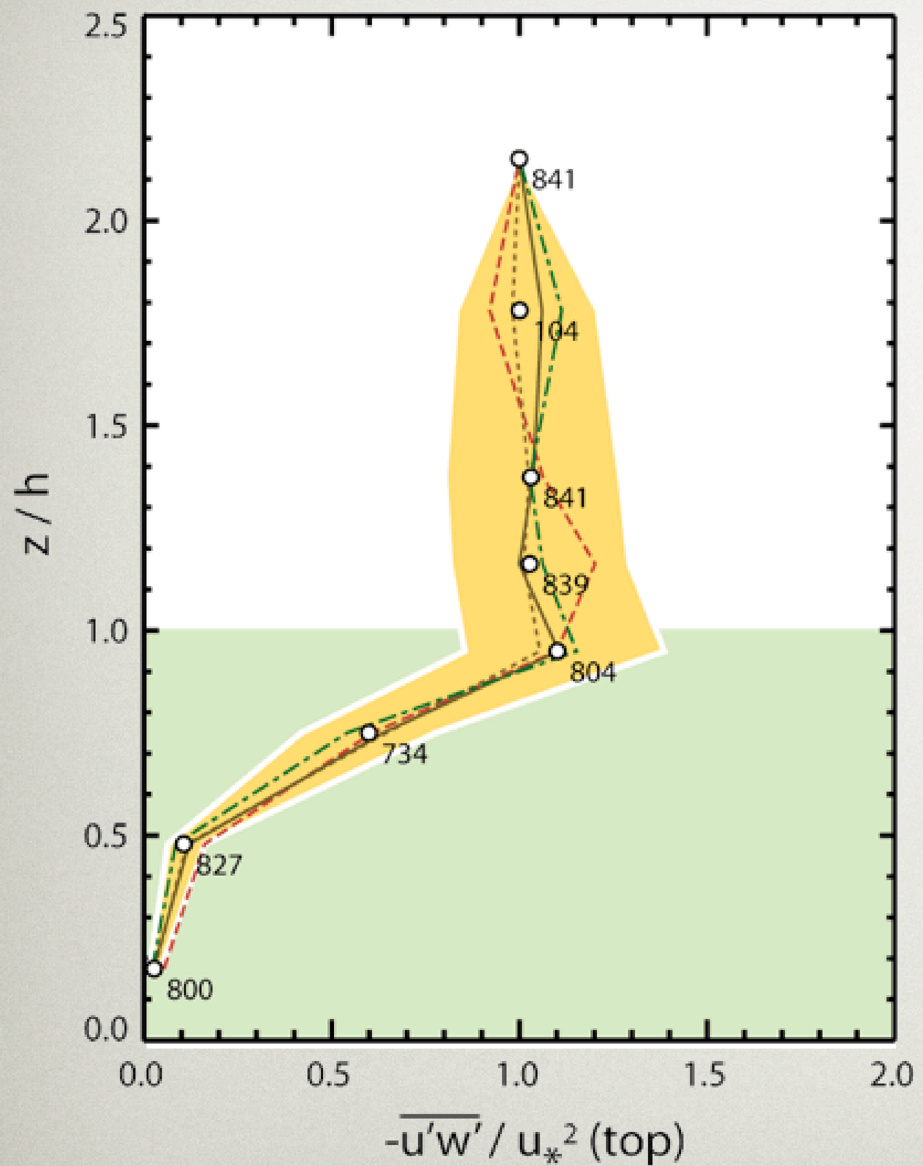
Vertical wind profile



Comparison to other studies



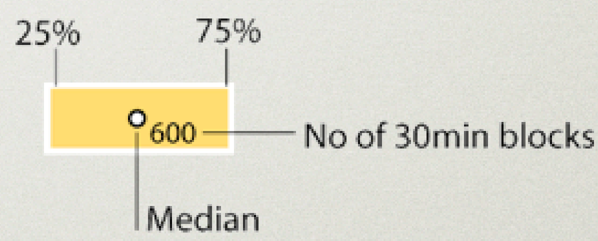
Reynolds stress



Selected stabilities (tower top)

- Convective (-10 < z/L (top) < -1)
- Unstable (-1 < z/L (top) < -0.05)
- Neutral (-0.05 < z/L (top) < +0.05)
- Stable (+0.05 < z/L (top) < +10)

All data



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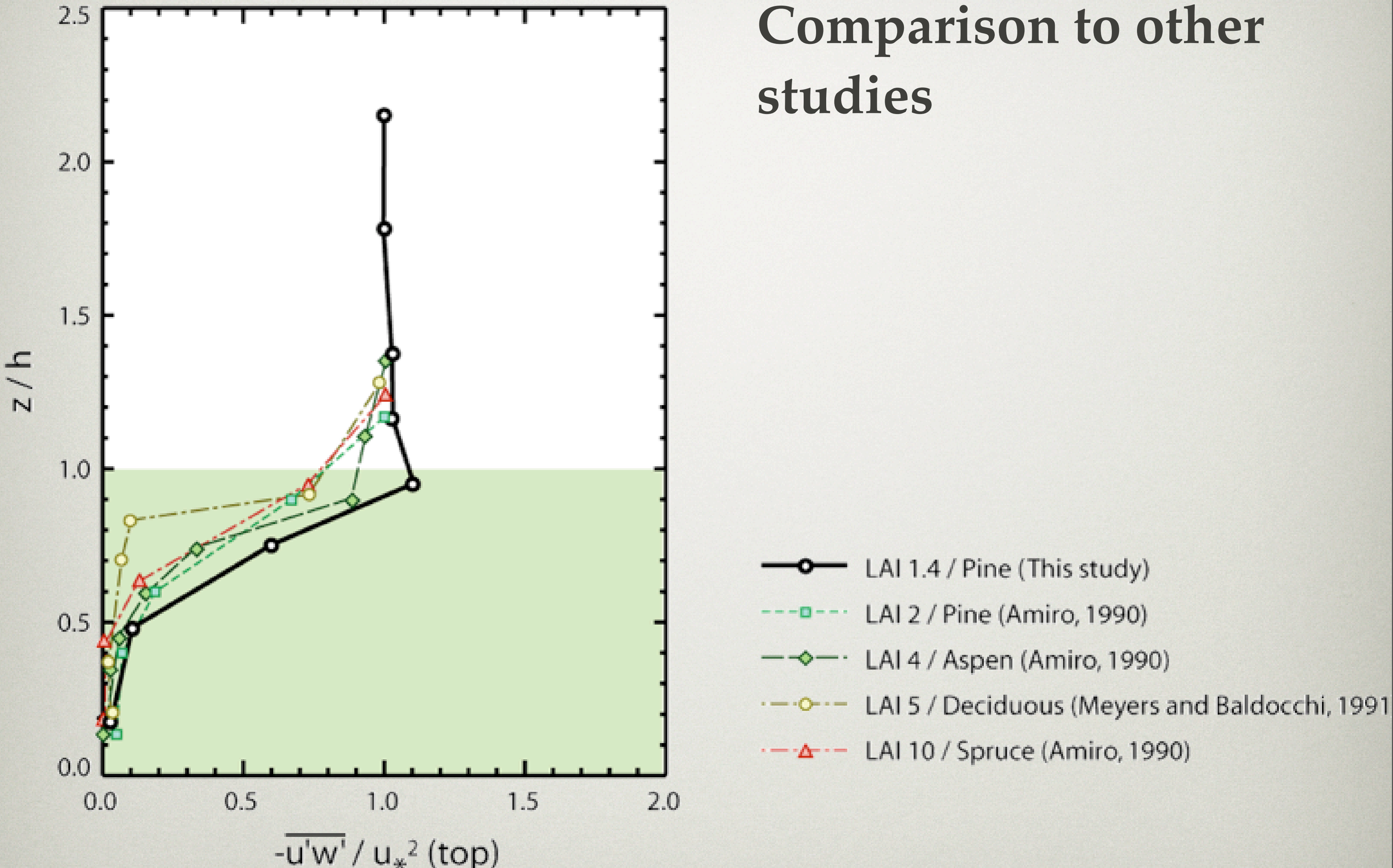
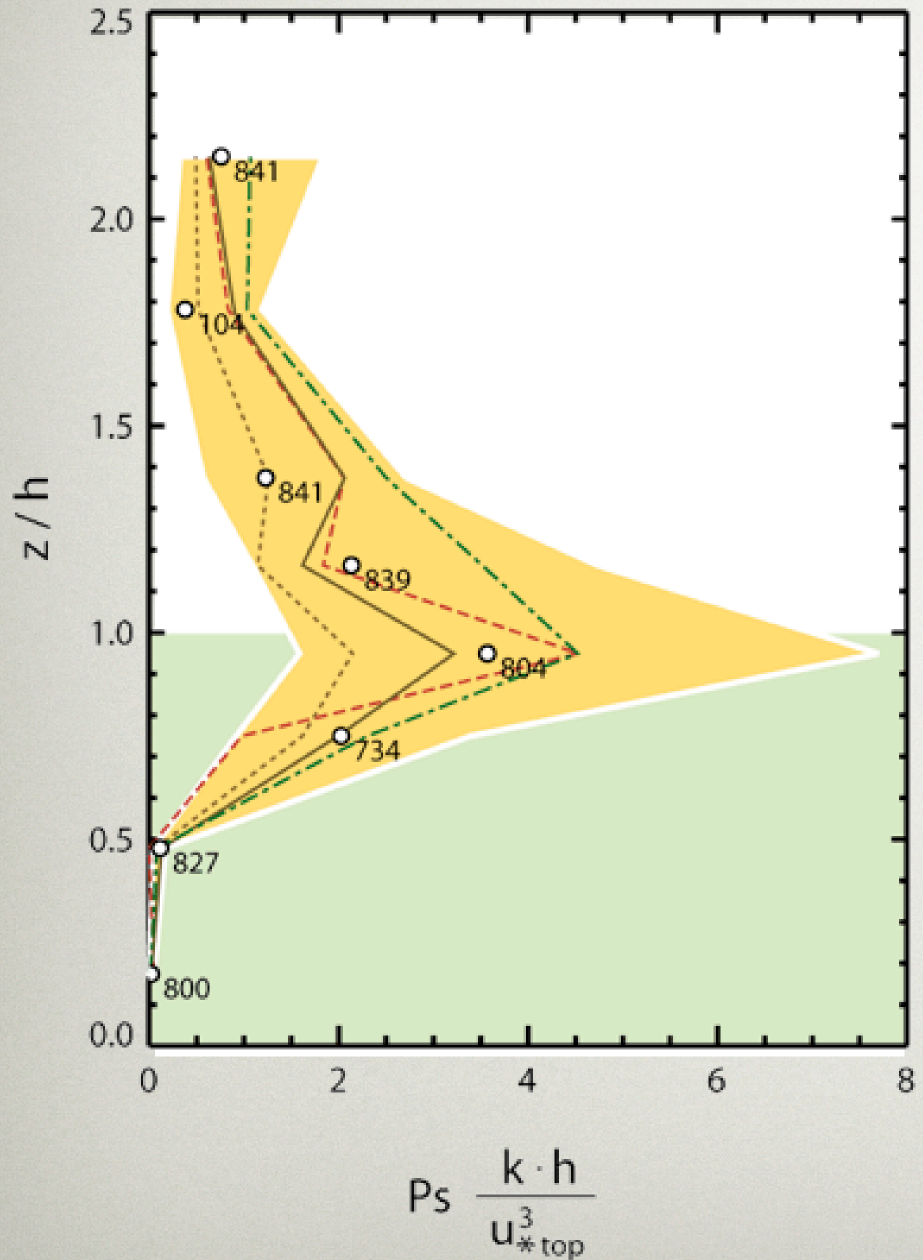


Shear Production

$$P_s = -\langle\overline{u'w'}\rangle \frac{\partial\langle\overline{u}\rangle}{\partial z}$$



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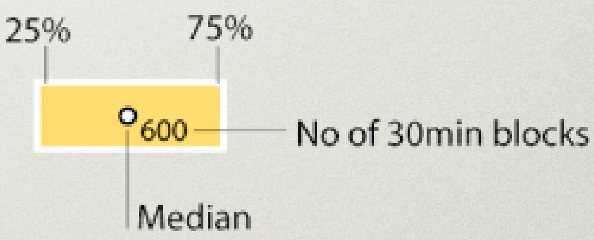
All data

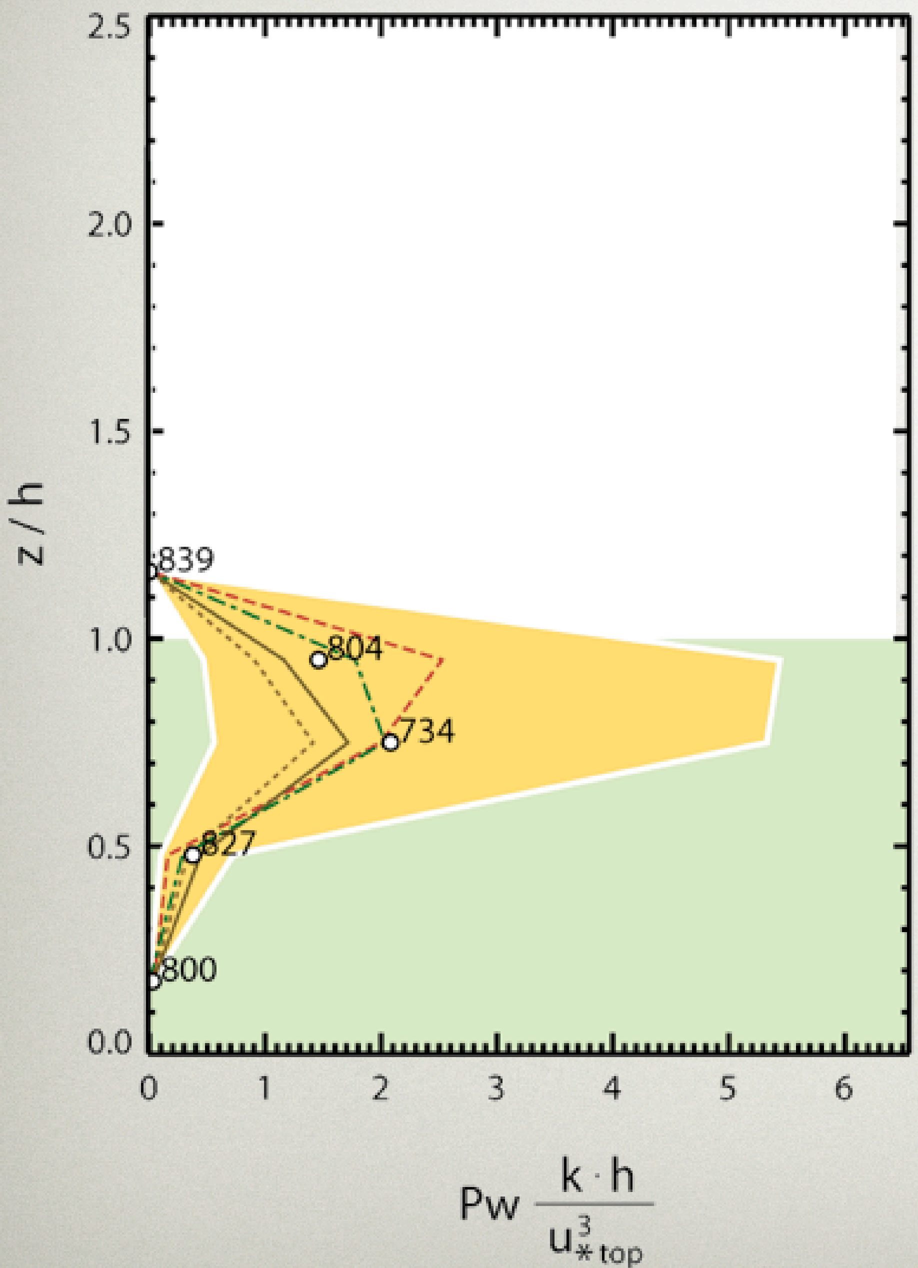


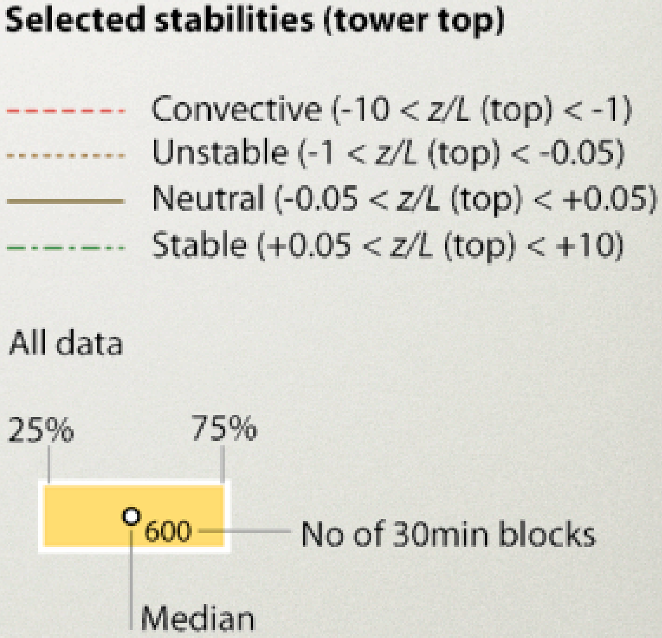
Shear Production

Wake Production

$$P_w = -\langle \overline{u} \rangle \frac{\partial \langle \overline{u'w'} \rangle}{\partial z}$$

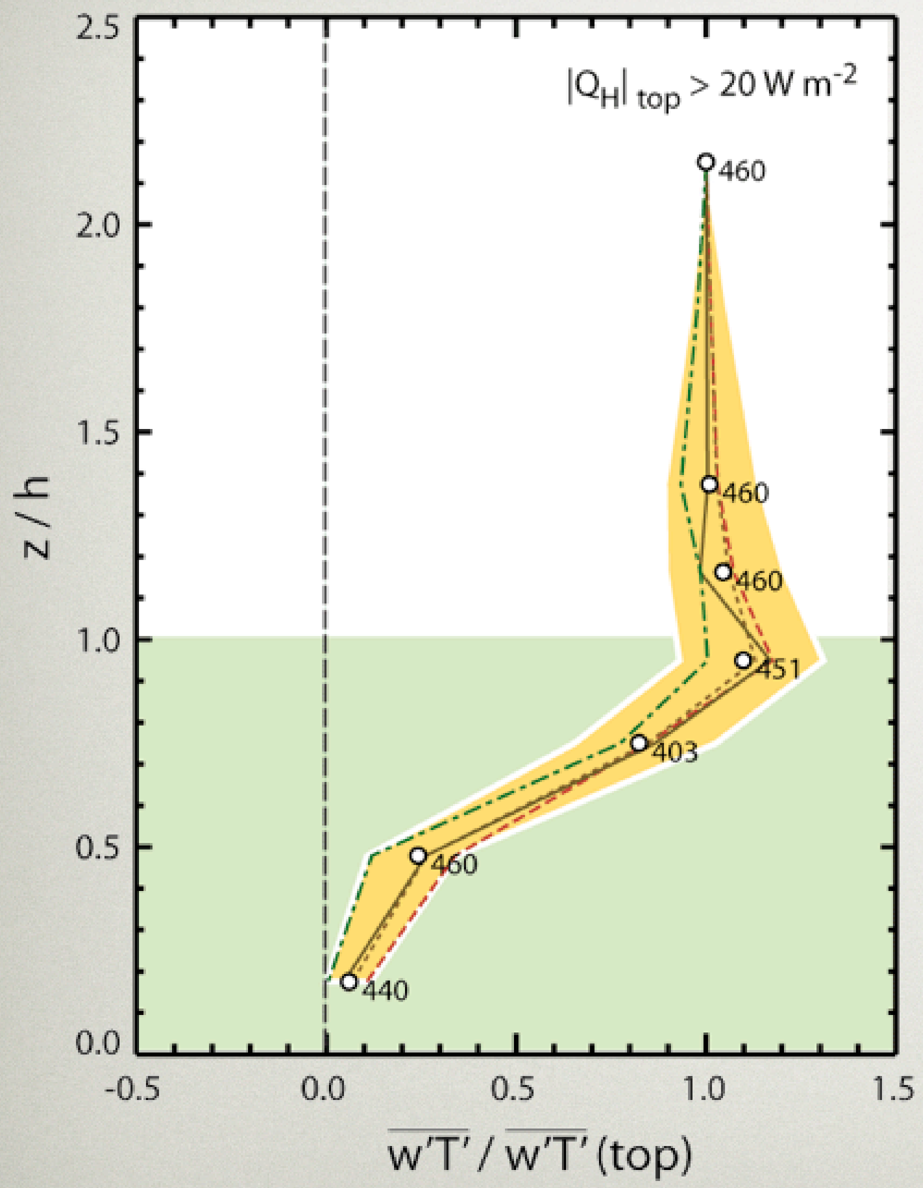
Raupach et al. (1986), *BLM.*, **35**, 21-55.





Wake Production

Sensible heat flux



Selected stabilities (tower top)

Convective (-10 < *z/L* (top) < -1)
Unstable (-1 < *z/L* (top) < -0.05)
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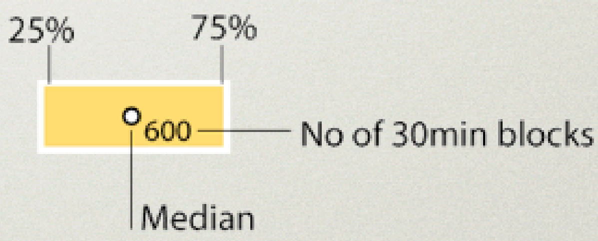
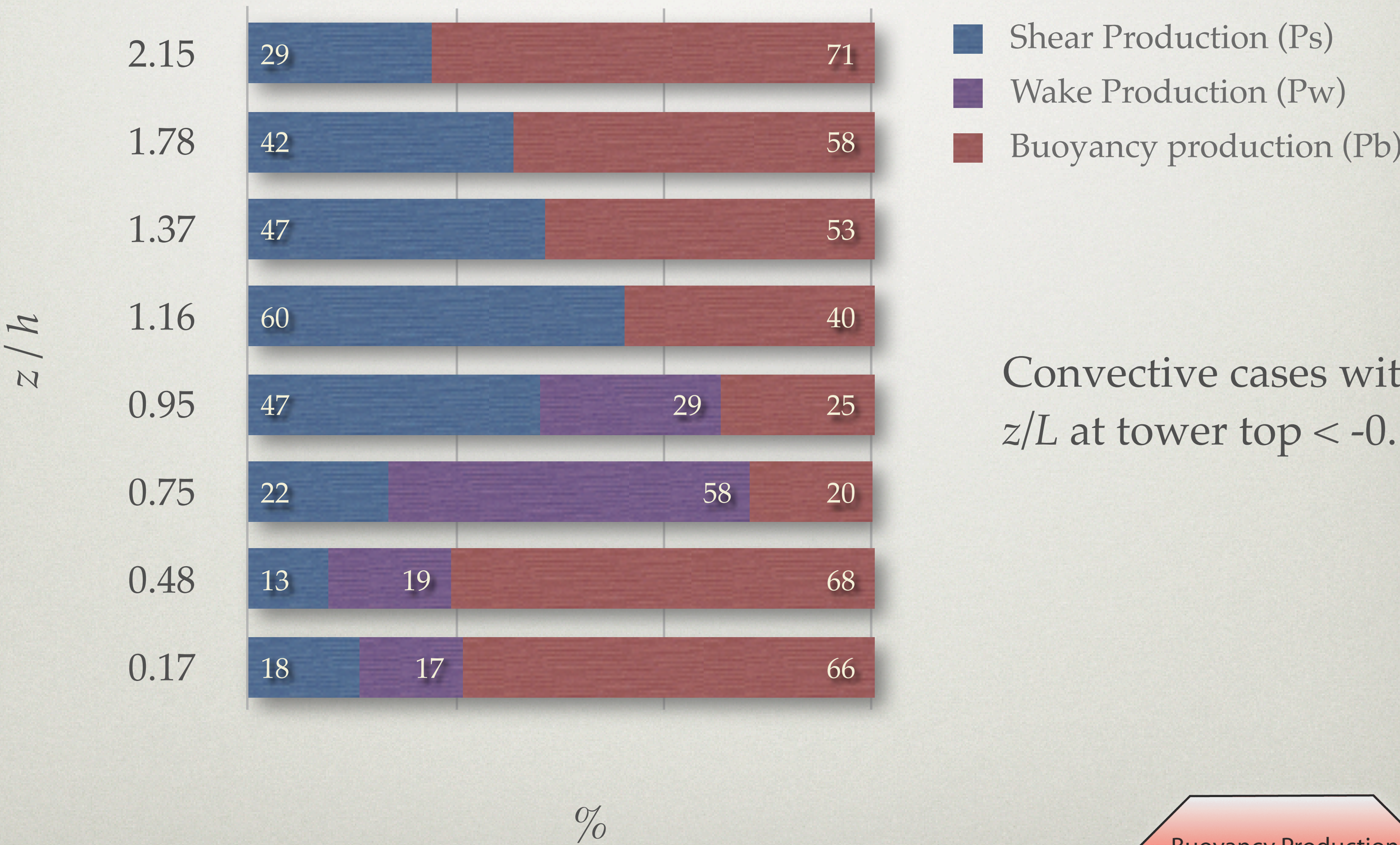
All data



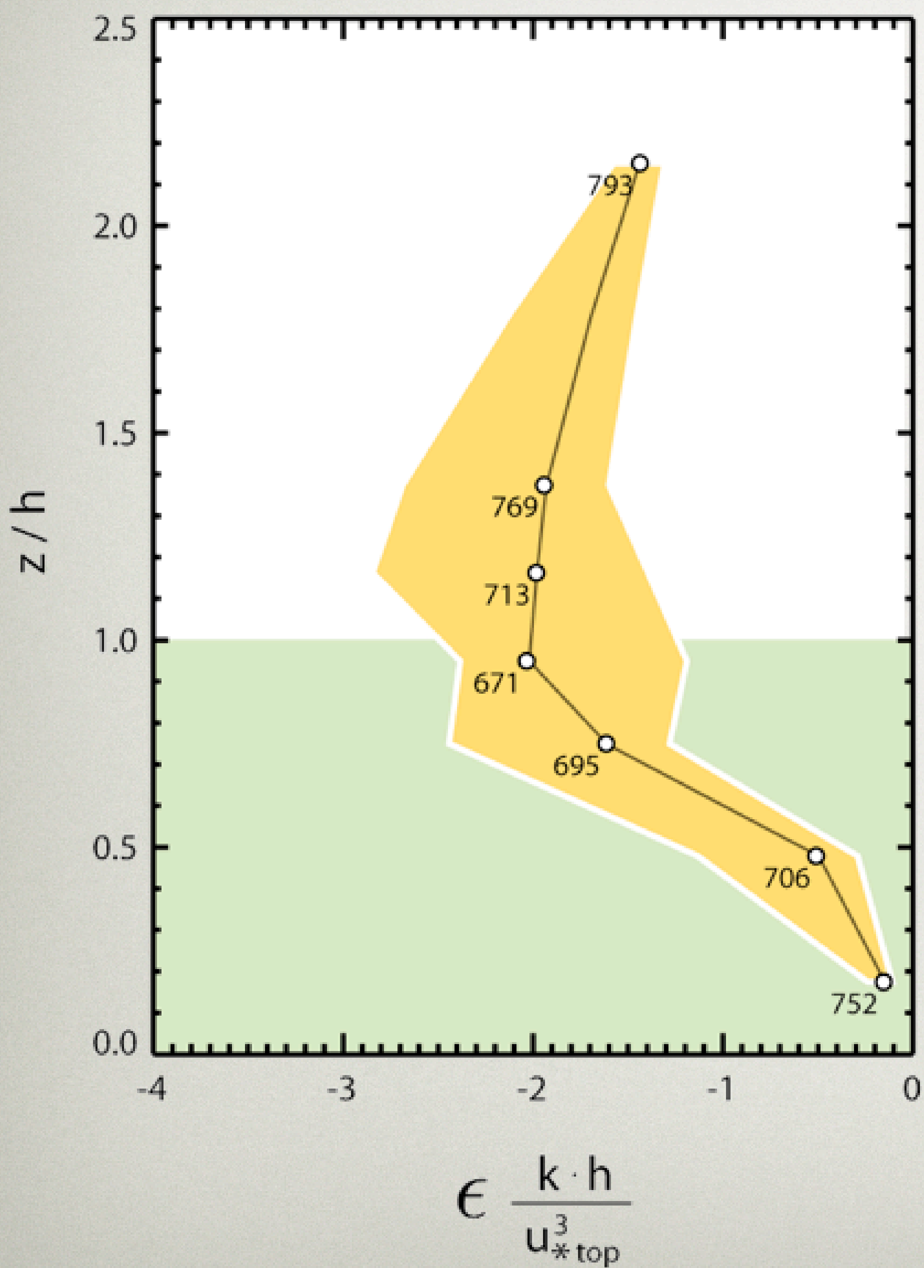
Buoyancy Production

TKE production for convective cases



Convective cases with
z/L at tower top < -0.1

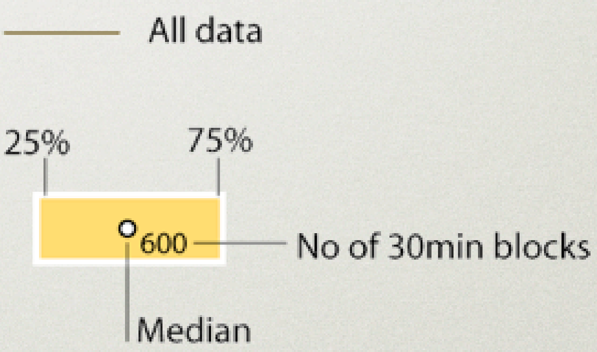
Buoyancy Production



Dissipation of TKE

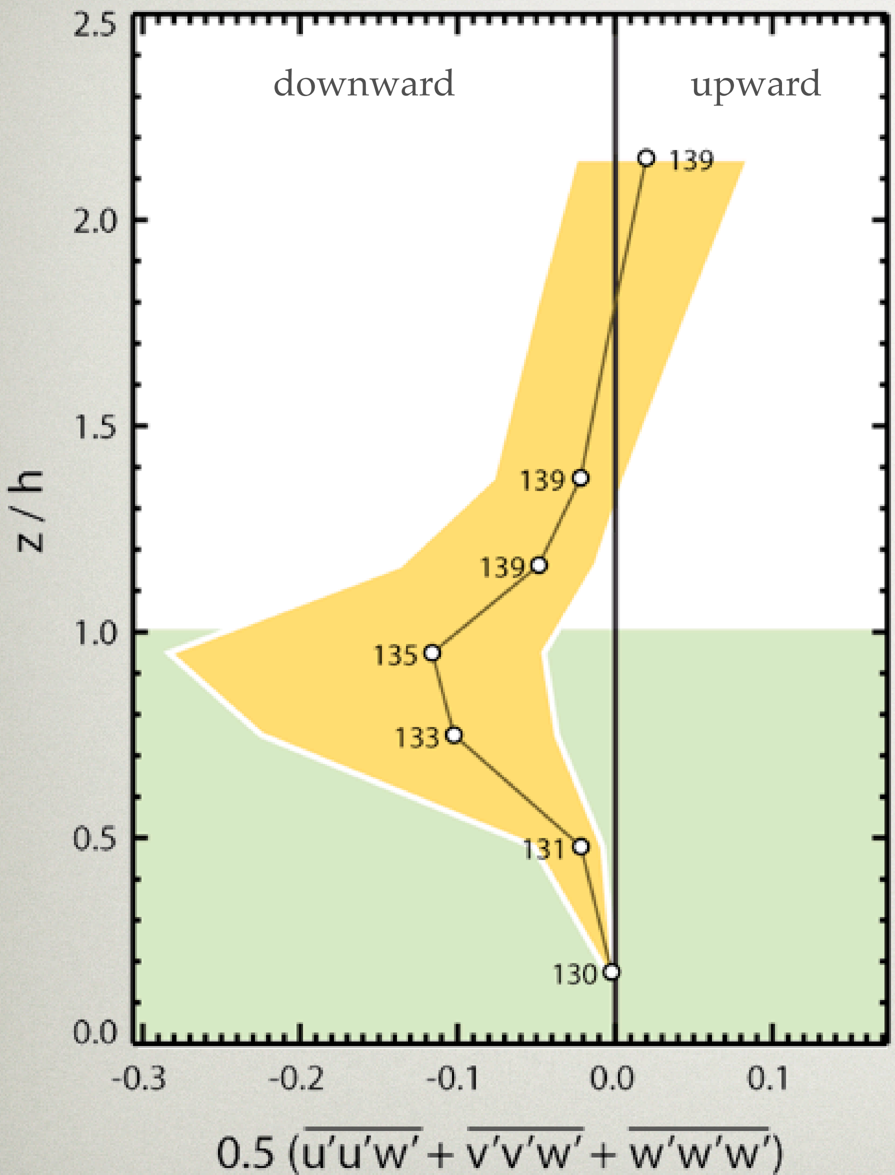
Based on 'regular' intertial subrange spectra (Kolmogorov).

No MKT (Finnigan, 2000)

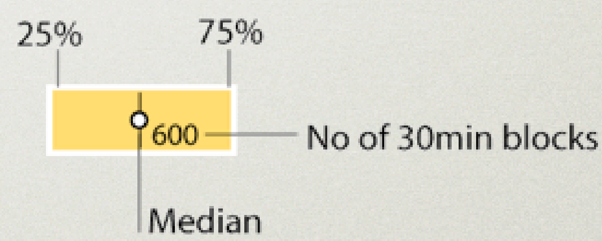


Dissipation

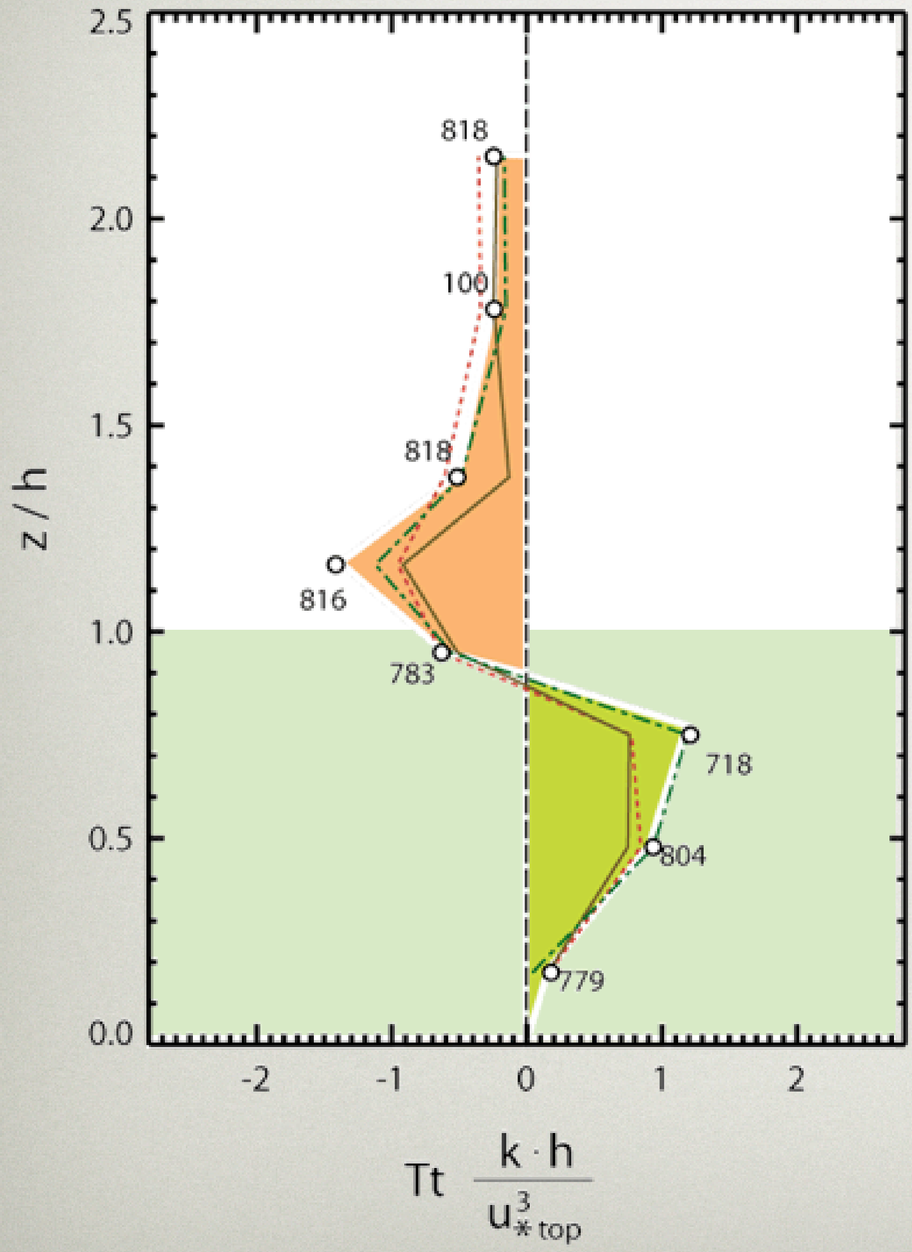
Vertical turbulent transport of TKE



Neutral (-0.05 < *z/L* (top) < +0.05)



Turbulent Transport



Divergence of turbulent transport (Tt)

$$T_t = -\frac{\partial \langle \overline{u_i' u_i' w'} \rangle / 2}{\partial z}$$

Net export of TKE

Net import of TKE

Selected stabilities (tower top)

Unstable (-1 < *z/L* (top) < -0.05)
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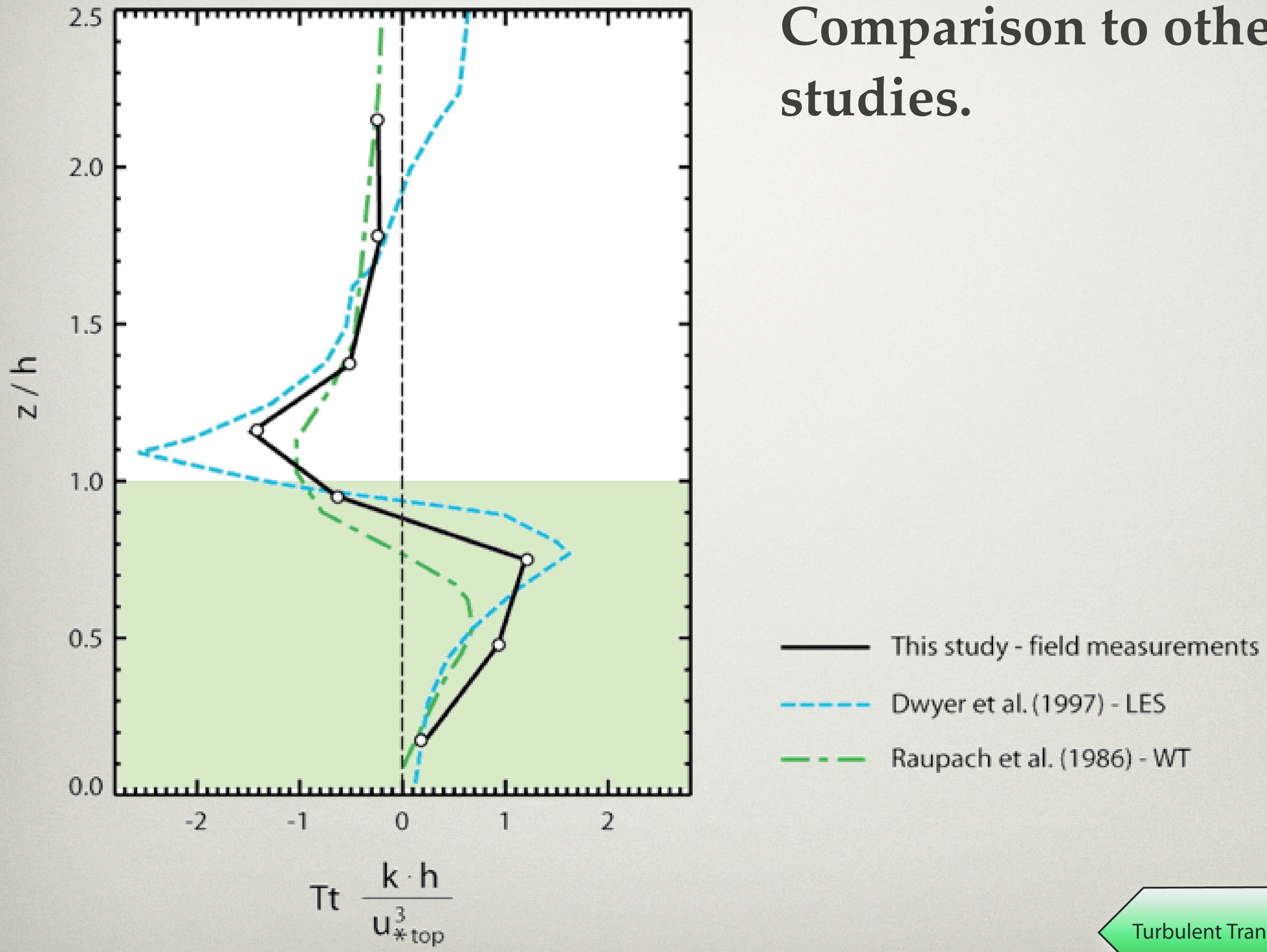
Stable (+0.05 < *z/L* (top) < +10)

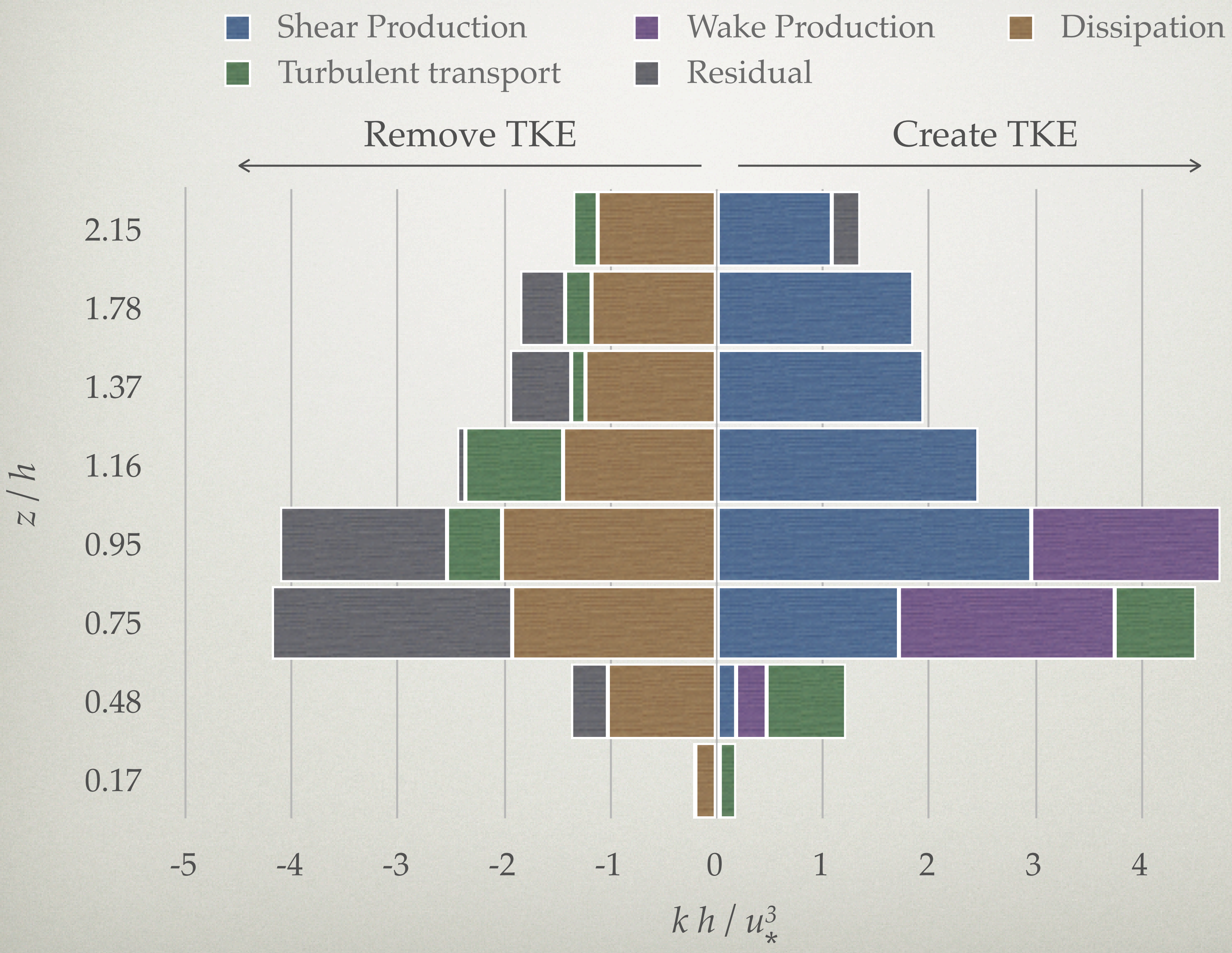
Turbulent Transport

Comparison to other studies.

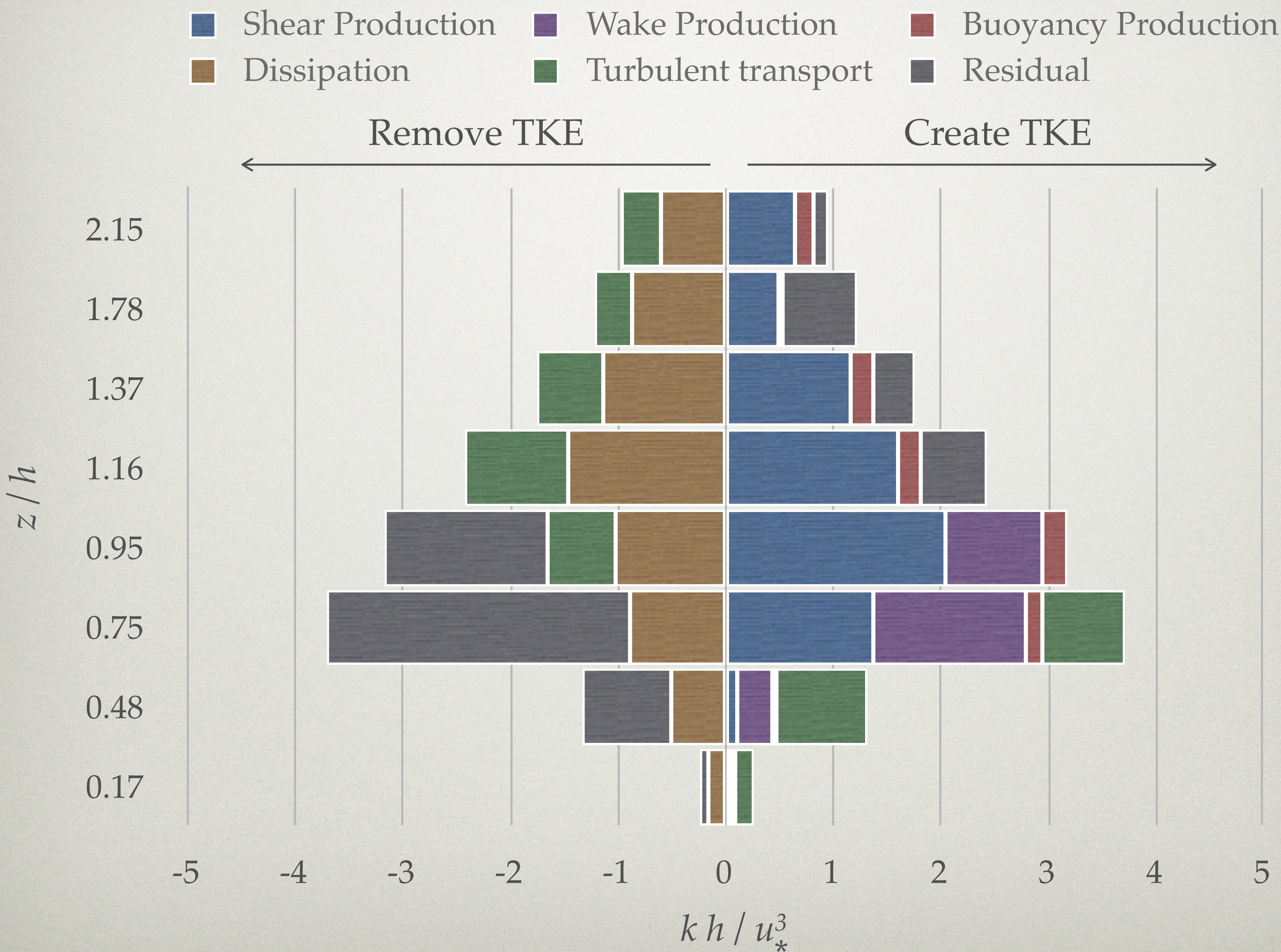


Turbulent Transport

Neutral TKE budget



Unstable TKE budget



Key findings

- **Shear production** dominates production with peak at canopy top $z / h = 0.96$ (inflection point). **Wake production** is most important at $z / h = 0.75$.
- On average, magnitude of **buoyancy production** (or suppression) is typically less than 15% of shear and wake production together.
- Excess turbulence from canopy top and above ($z/h > 0.9$) is exported down to the canopy and trunk space ($z/h < 0.9$) by **turbulent transport** of TKE.
- Residual term indicates that **pressure transport** relocates excess TKE from upper canopy and canopy top to higher layers of the atmosphere.

Discussion

TKE budget does not differ significantly from dense canopies, however some points are notable:

- Shear and wake production are important in the whole upper canopy (i.e. above $z/h < 0.5$), not just at canopy top.
- Normalized peak shear production is ~4, which is lower compared to other forests (6 in Leclerc *et al.*, 1990; 20 in Meyers and Baldocchi, 1991).
- Turbulent transport is dominating source in the lower trunk space.
- The residual term indicates that likely pressure transport is removing TKE from upper canopy to higher layers - this observation is supported by LES results (Dwyer *et al.*, 1997).

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