Higher-order statistics of the turbulent flow in a sparse Lodgepole Pine canopy

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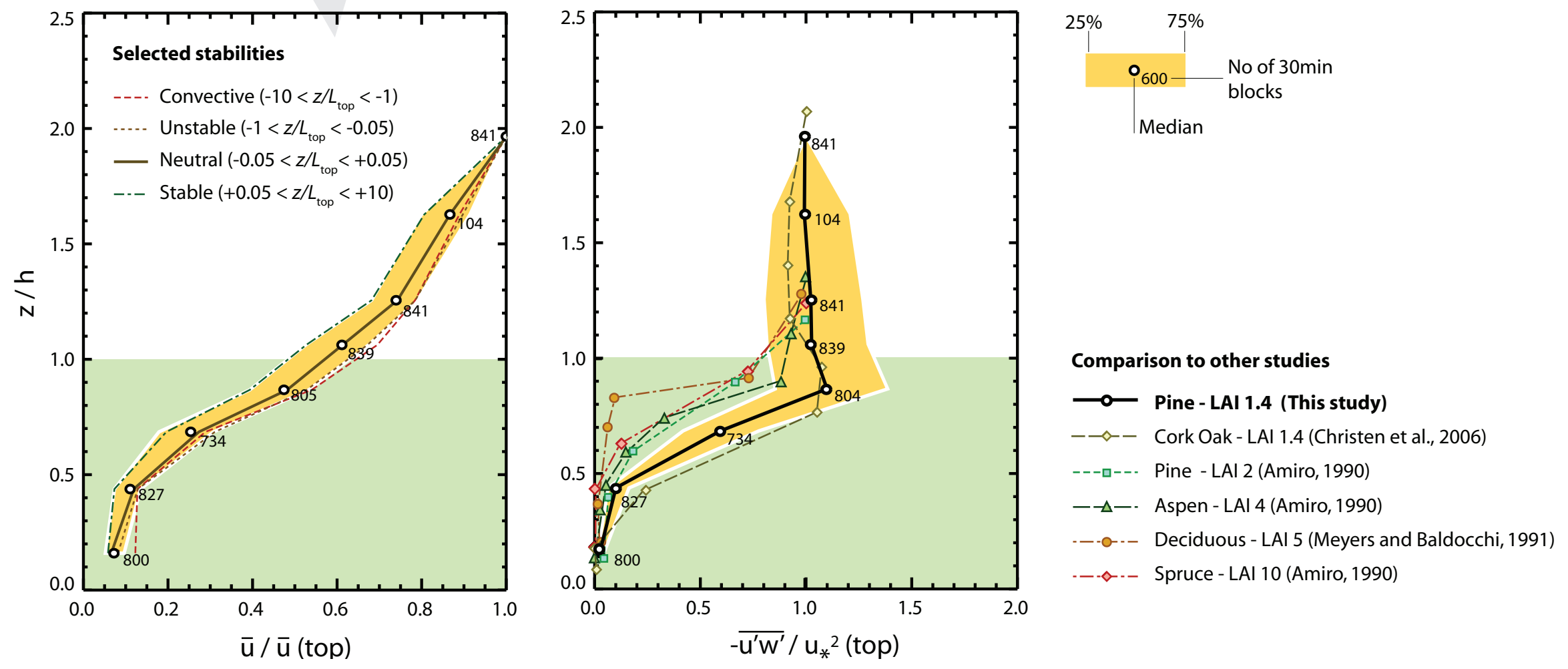
An accurate modeling of plant-atmosphere interactions relies on an appropriate implementation of canopy turbulence. In the roughness sublayer of forests we encounter conditions that result in non-zero 3rd order moments and hence strongly skewed probability density distributions.

Describing relationships and simplifications is complicated by the extreme range of canopy morphologies. Interestingly, most studies done so far (field, wind-tunnel, and flume experiments, but also numerical simulations) focussed on dense canopies. Less information has been published on sparse canopies even though they form a significant part of the global land surfaces - in particular in the boreal zone. Are any previously reported findings for higher-order moments applicable in sparse canopies?

Experimental set-up.

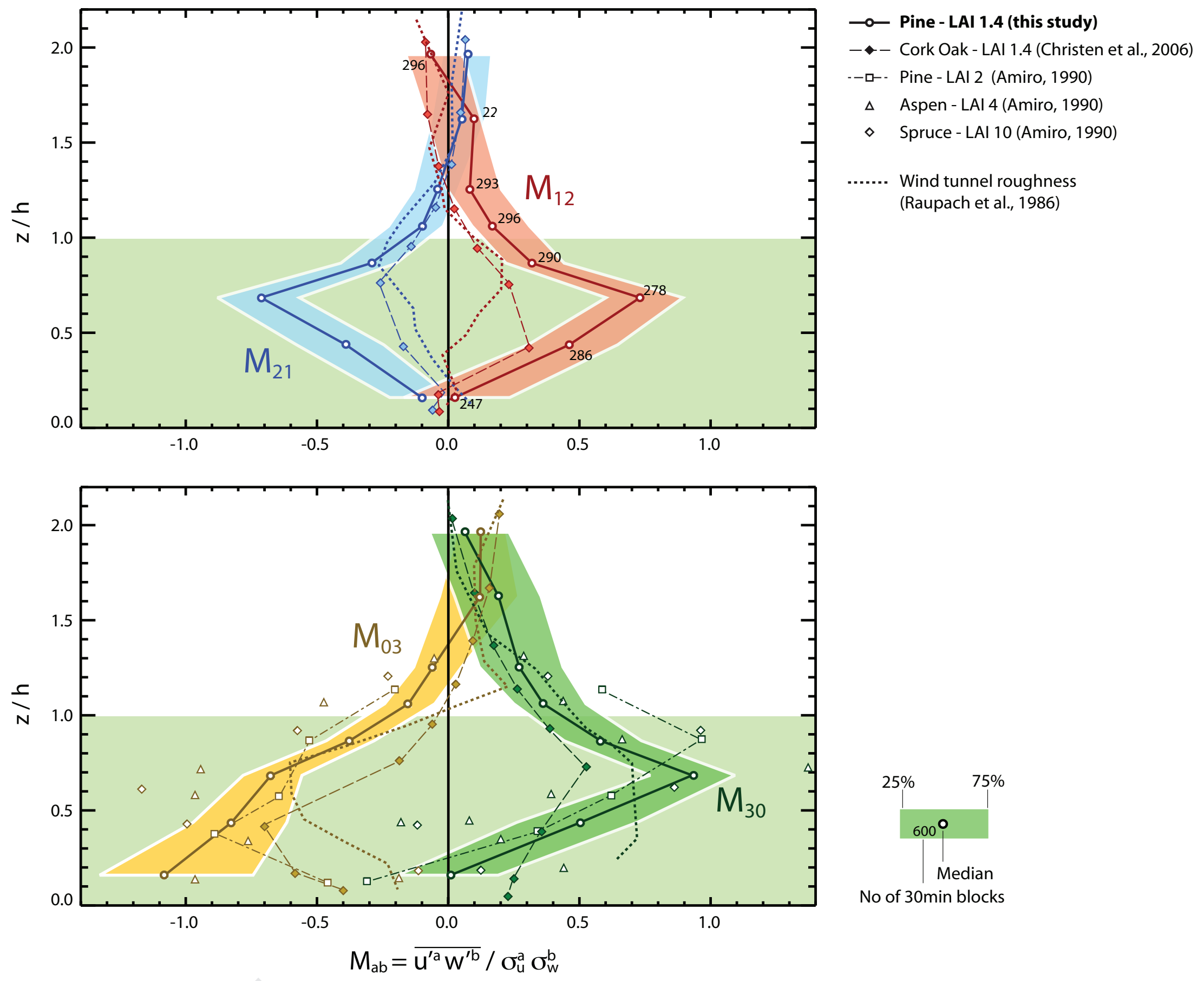
This question has been addressed in a recent field experiment in a sparse Lodgepole Pine stand in Central British Columbia, Canada. Data was sampled using a vertical array of ultrasonic anemometers at the 'Kennedy Siding' tower (55° 06' 43"N, 122° 50' 23"W). Eight Campbell Scientific CSAT-3 ultrasonic anemometers were simultaneously operated at 10 Hz at different heights (z/h = 0.16, 0.44, 0.68, 0.87,1.06, 1.25, 1.56, and 1.96) over one month in August / September 2007. The stand surrounding the tower has a mean canopy height of h = 16 m, a low canopy cover of only 24.3%, and a leaf area index of 1.38. The site is located in flat terrain and the fetch in all wind directions extends to at least 1 km.

Wind profile and Reynolds stress - In agreement with observations in denser forests, the wind profile is characterized by a distinct inflection point in the upper canopy (left). Reynolds stress $\overline{u'w'}$ does not decrease as effectively as within dense forests - and remains a significant term in the upper third of the canopy (right).

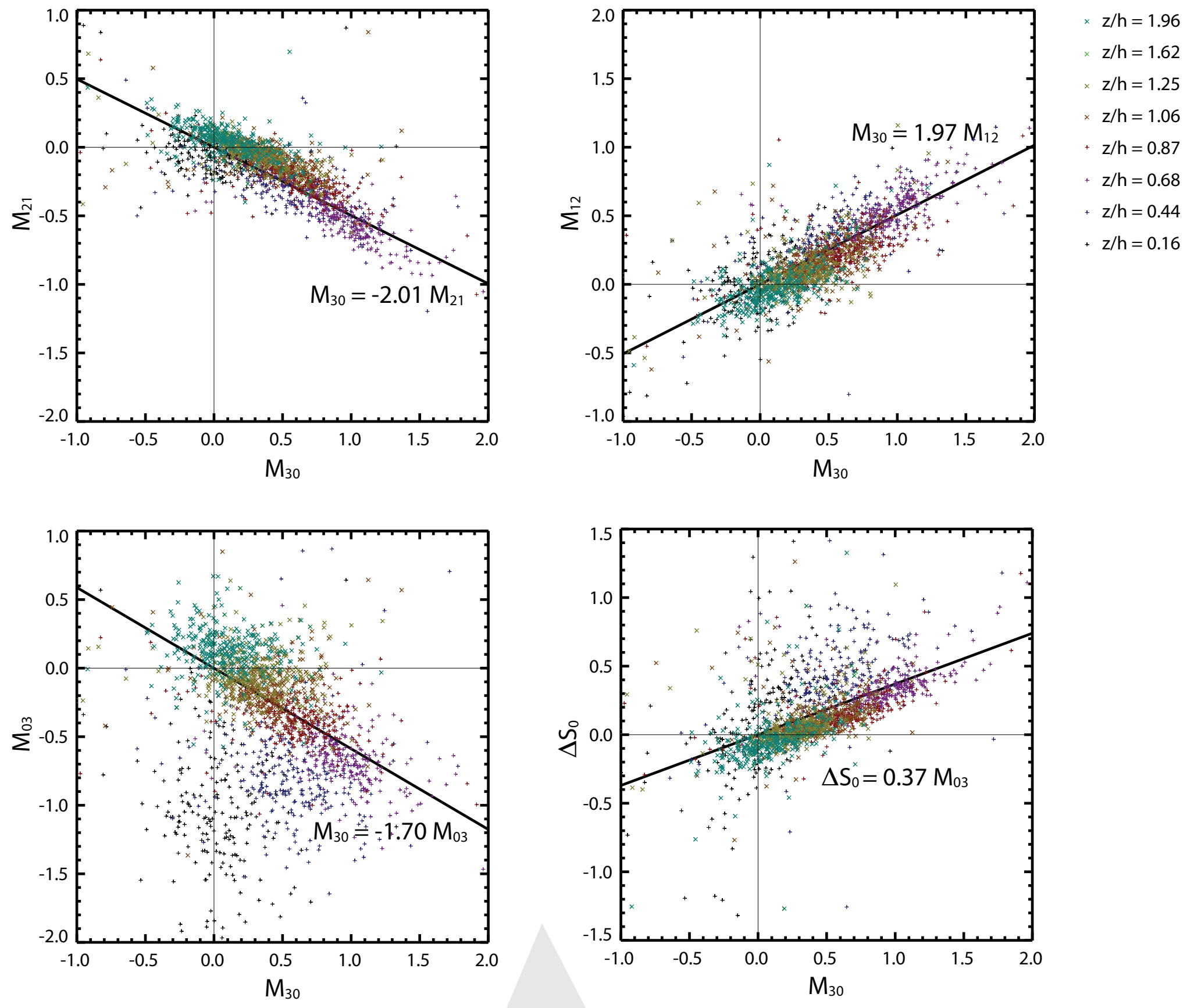


3rd order velocity moments.

In contrast to Gaussian turbulence, 3rd order moments are significant throughout the whole roughness sublayer - and in particular within the forest canopy. Previous studies revealed 'universal' roughness sublayer relationships between higher order moments, and concluded that considering moments up to order three is sufficient. Are those findings confirmed by the data from this sparse canopy?



Normalized 3rd order moments - The normalized velocity triple moments $M_{ab} = \overline{u'^a w'^b} / (\sigma_u^{\ a} \sigma_w^{\ b})$ with $a + b = 3$ show characteristic profiles throughout the roughness sublayer of the pine stand which do not significantly differ from previous studies. But M_{12} and M_{21} show higher peak values in the central canopy.

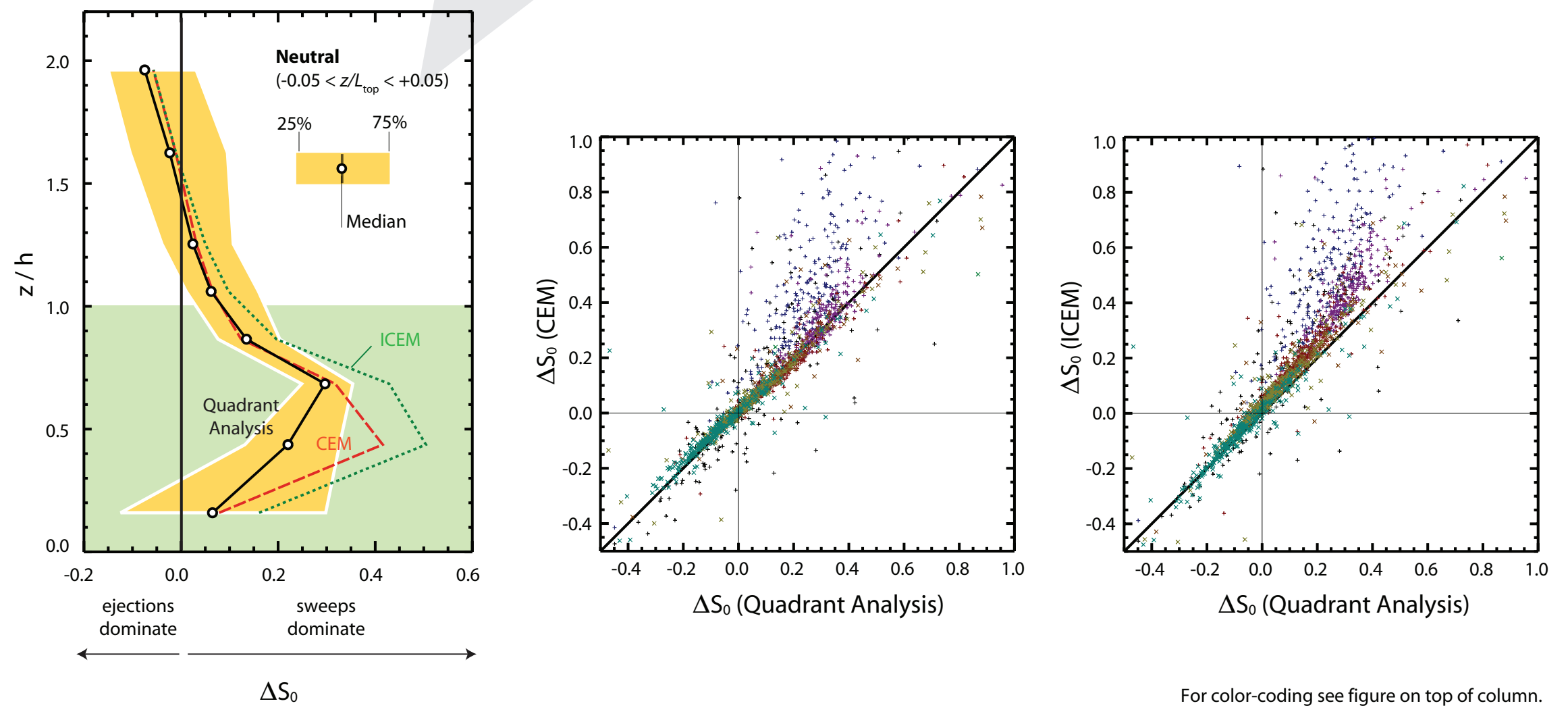


Roughness sublayer relationships determined in the wind tunnel by Raupach (1981, black lines) agree reasonable with the data observed in this sparse canopy. Most critical is the trunk space region where low velocities and - likely higher order moments (see below) - affect the relationship between M_{30} and M_{03}.

3rd order moments and the sweep-ejection cycle.

To refine the analysis of the transport of momentum, quadrant analysis is used to separate the total flux into four stress fractions, most importantly the transport of momentum deficit upwards $S_{i,2}$ (ejections) and momentum excess downwards $S_{i,4}$ (sweeps). The difference between those is expressed by $\Delta S_0 = S_{i,4}\text{-}S_{i,2}$, a parameter which theoretically includes all moments up to infinity, but except in the middle trunk space (z/h = 0.44) a 'cut-off' at moments of order 3 allows a reasonable approximation.

Are 3rd order moments sufficient to appropriately describe ΔS_0 in this sparse canopy? A 3rd order Cumulant Expansion (CEM, Nakagawa and Nezu, 1977) is a stringent test that clearly supports this assumption except at z/h = 0.44. The simpler, incomplete CEM (ICEM, Katul *et al.*, 1997) shows a systematic overestimation in the whole vertical domain.

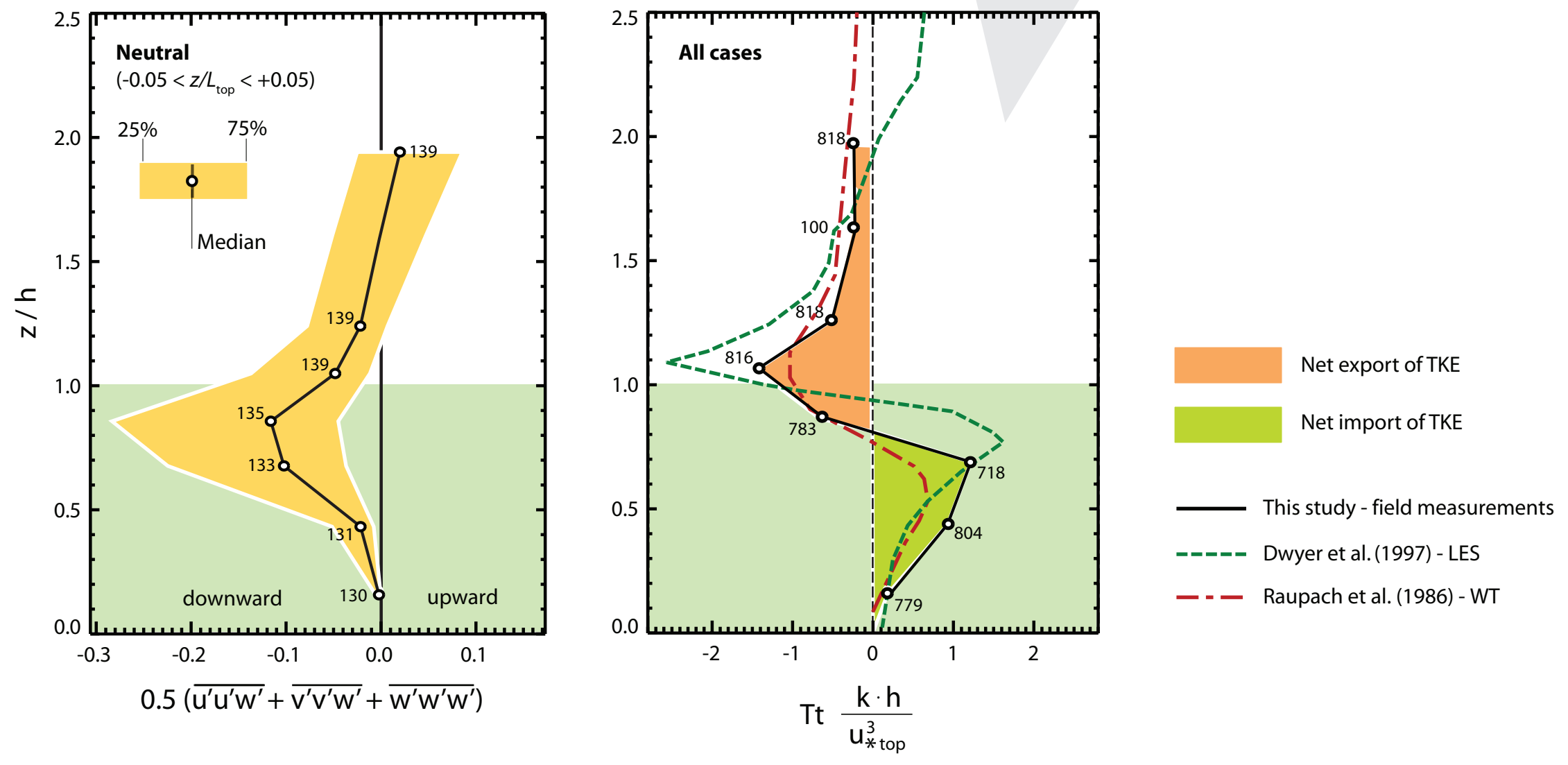


For color-coding see figure on top of column.

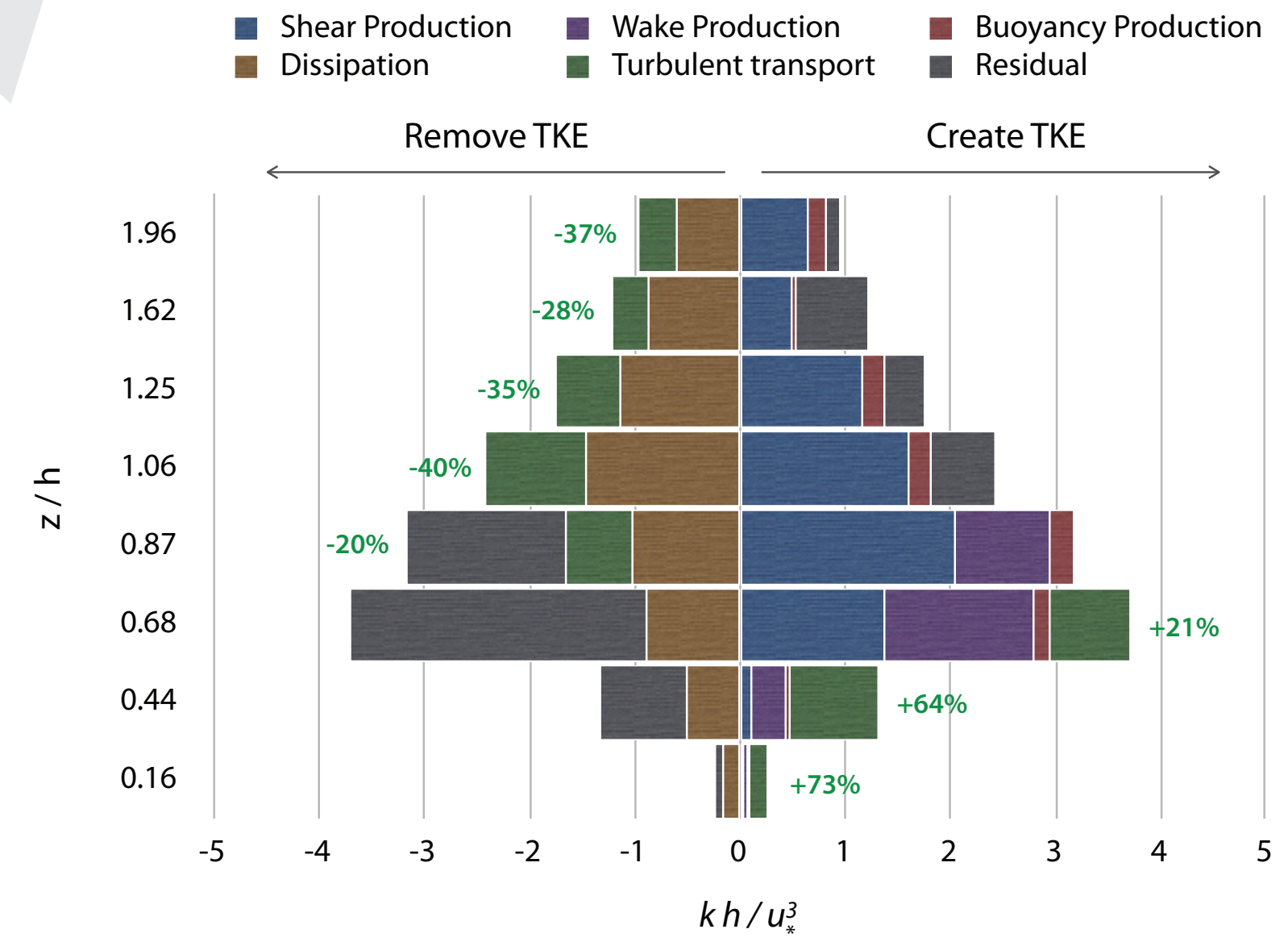
The role of 3rd order moments in the TKE budget.

In the roughness sublayer, 3rd order moments play a crucial role in the budget of turbulent kinetic energy (TKE). The turbulent transport term - described by the vertical divergence of $\overline{u_i'u_i'w'}$ - is a significant transport process controlling local turbulence in the canopy.

Turbulent transport of TKE - With the exception of the topmost measurement level, TKE is transported downward (left). The divergence of the vertical flux densities of TKE (right) indicates that excess turbulence from canopy top and above (z/h > 0.8) is exported to the canopy and trunk space (z/h < 0.8).



The importance of the turbulent transport term - The following figure illustrates the importance of the various terms in the TKE budget that create, relocate and destroy TKE. Turbulent transport of TKE (green bars) forms the biggest source in the lower trunk space and is a significant sink above.



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