Turbulence Spectra, Dissipation and Turbulent Kinetic Energy Budgets in the Stable Boundary Layer over Inhomogeneous Terrain

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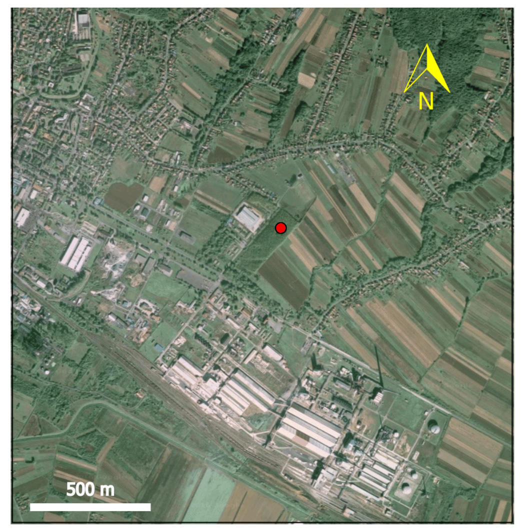
Objectives

- To investigate turbulence spectral characteristics within and above the roughness sublayer.
- To obtain the appropriate scaling parameters needed to collapse spectra.
- To compare spectra with existing models valid for the horizontally homogeneous and flat (HHF) terrain.
- To determine the influence of the tall canopy and heterogeneous surface cover on the TKE budget terms.

Site & Data

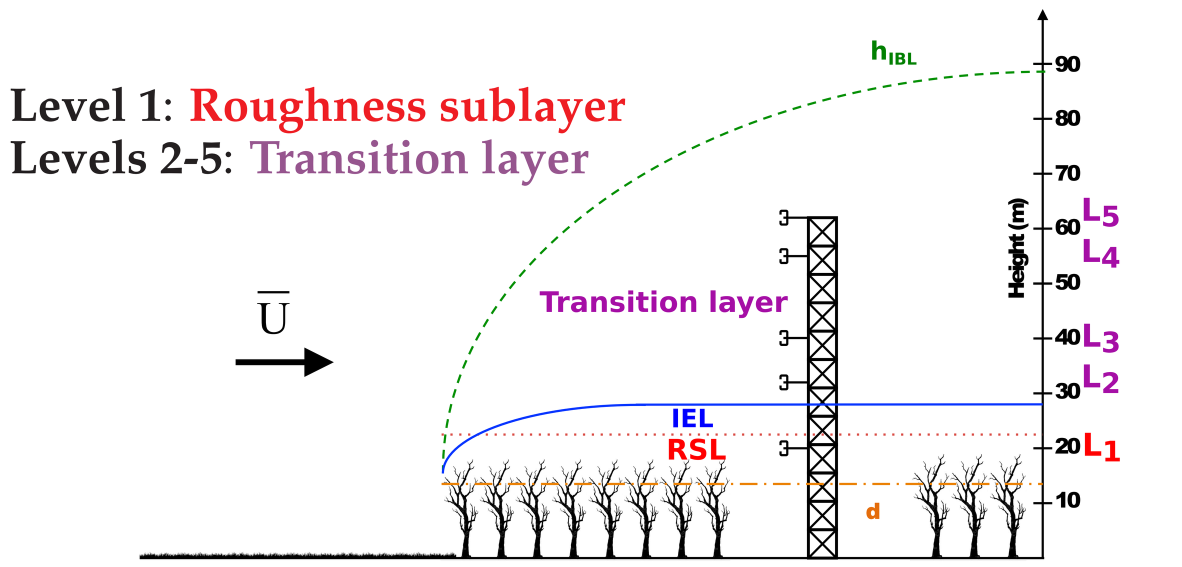


Data: from 62 m tower

- Five levels @ 20, 32, 40, 55 and 62 m
- Analyzed period: Dec 2008 - Feb 2009
- Nocturnal BL: 1800 - 0600 LST
- Canopy height ~ 18 m

Figure 1: Google Maps image (Image©2015 DigitalGlobe) of the observational site. Measurement tower is indicated with a red dot (45°28′32″ N, 16°47′44″ E).

Conceptual sketch of idealized vertical layers after a step change in surface roughness.



Babić et al. (2016)

Methods

Spectral models:

1. **Canopy scaling** (Kaimal and Finnigan, 1994)
2. **Kaimal et al. (1972)** (neutral)

$$\frac{fS_{u,v}}{u_*^2} = \frac{An}{(1+Bn)^{5/3}}, \quad \frac{fS_w}{u_*^2} = \frac{An}{1+Bn^{5/3}} \tag{1}$$

3. **Olesen et al. (1984)** (stable)

$$\frac{fS_{u,v,w}}{u_*^2} = \frac{A(n/\phi_m)}{1+B\,(n/\phi_m)^{5/3}}\left(\frac{\phi_\varepsilon}{\phi_m}\right)^{2/3} \tag{2}$$

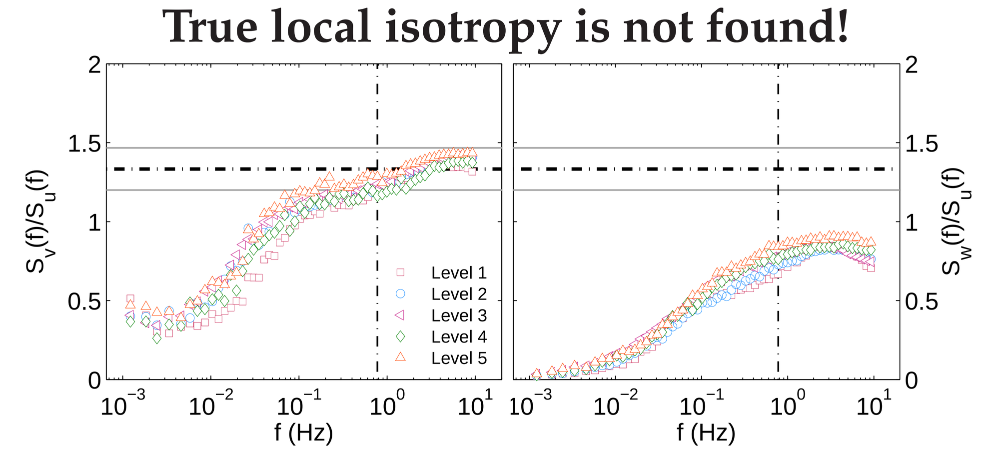
Normalized TKE budget equation:

$$0 = \phi_a + \phi_m - \zeta - \phi_t - \phi_p - \phi_\varepsilon \tag{3}$$

TKE Dissipation Rate

Local Isotropy Requirements: $S_{w,v}/S_u = 4/3$ and $-5/3$ slope within the inertial subrange

True local isotropy is not found!



- $S_w < S_u, S_v$ as well as $\phi_{\varepsilon w} < \phi_{\varepsilon u,v} \Longrightarrow$ **important** for normalization of S_w

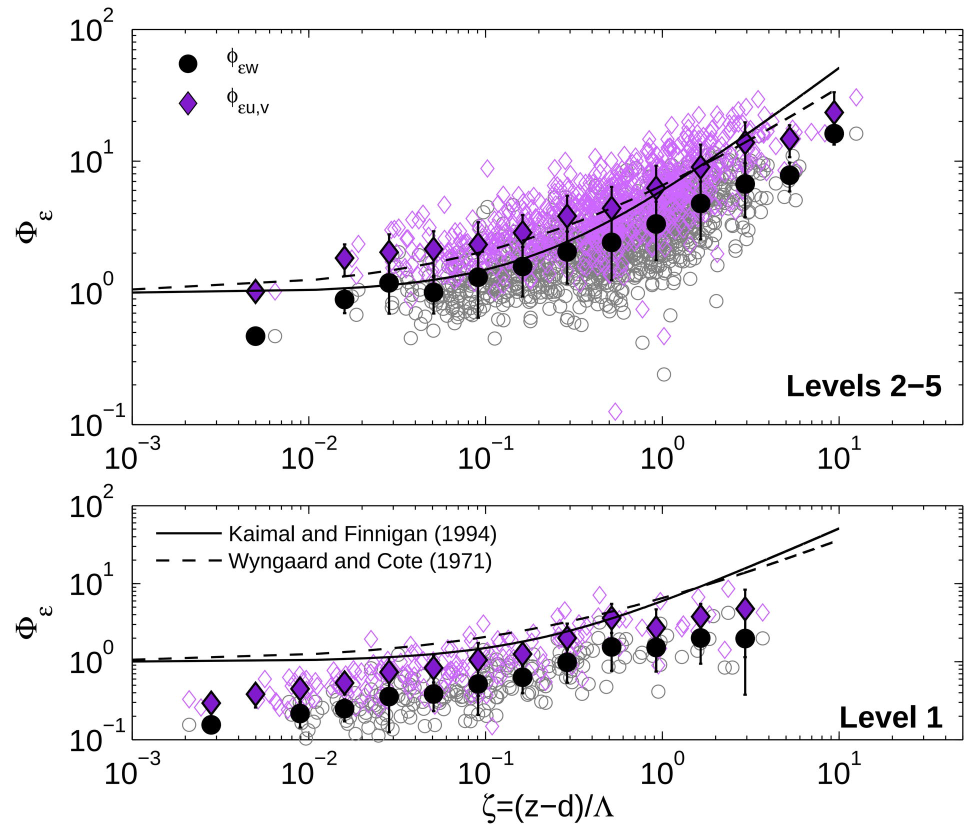


Figure 2: Non-dimensional dissipation rate of the TKE ($\phi_\varepsilon = k(z-d)\varepsilon/u_{*\ell}^3$) versus local stability parameter ζ, where $\Lambda = -u_{*\ell}^3\overline{\theta_v}/(kg\overline{w'\theta_v'})$ is local Obukhov length.

Characteristics of the Velocity Spectra

Canopy scaling: $fS_{u,v,w}/\sigma_{u,v,w}$ vs. fh_c/U_{hc}

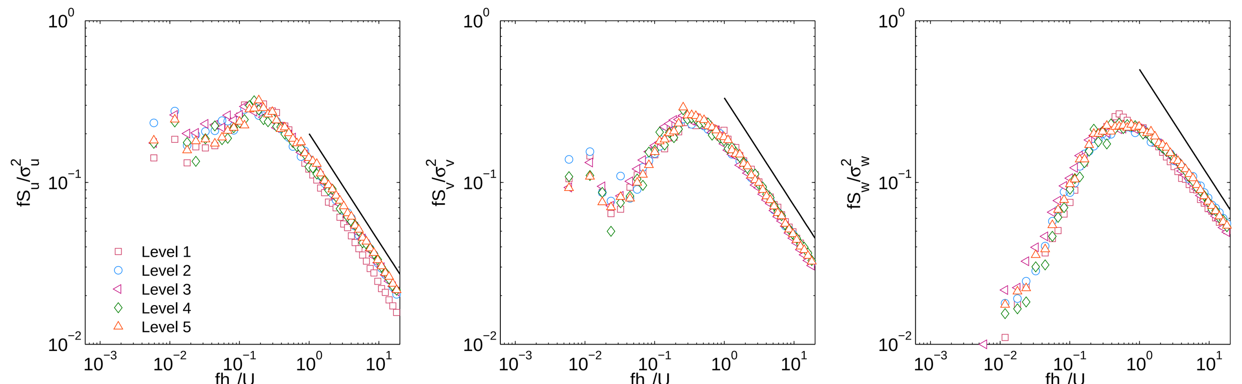


Figure 3: Normalized spectra of all three velocity components at all five levels (median of all spectra is shown) plotted versus frequency normalized with canopy scaling (h_c and U_{hc}). Solid black line denotes $-2/3$ slope (**inertial subrange**).

- **Canopy scaling** $(\sigma_{u,v,w}, U_{hc}, h_c)$ was successful through the entire measurement layer.
- Vertical spectra normalized with $\phi_{\varepsilon w} \Longrightarrow$ good correspondence with the Kansas (& Minnesota) spectral models.
- Spectral models of Olesen et al. (1984) for the first time applied to data over heterogeneous plant canopy and found to be successful.
- Influence of sub-meso motions evident in S_u, S_v spectra at lower frequencies.

Spectral model according to Kaimal et al. (1972)

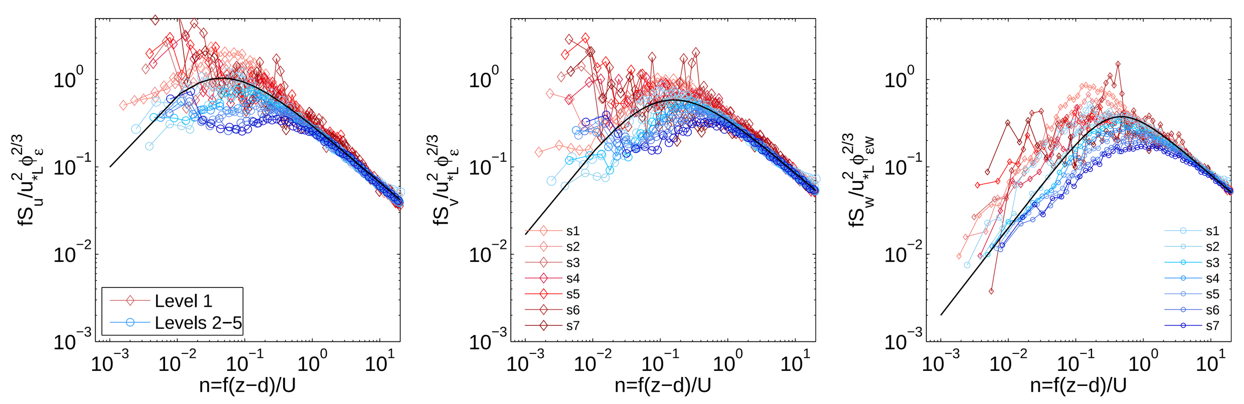


Figure 4: Normalized spectra of all three velocity components for seven different stability categories (median of all spectra is plotted). Black solid curves → neutral Kansas spectra Kaimal et al. (1972).

Spectral model according to Olesen et al. (1984)

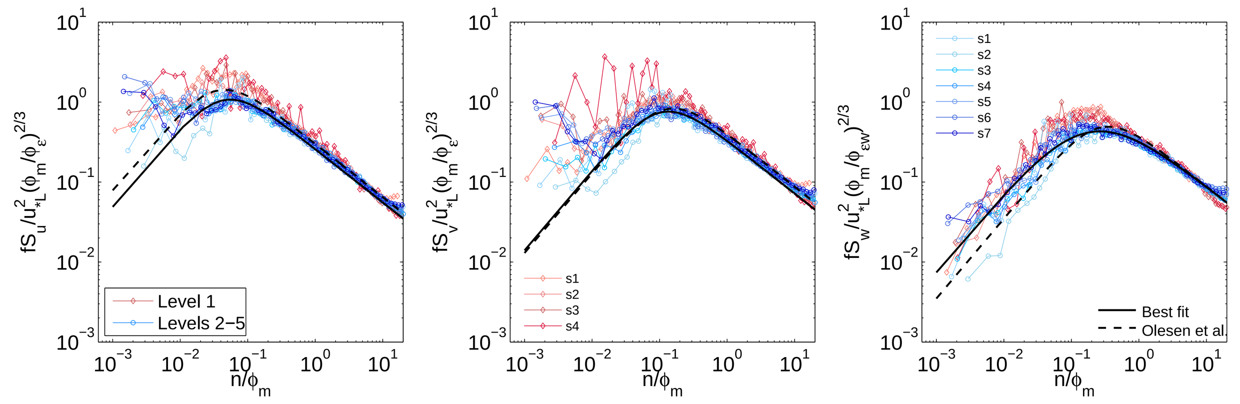


Figure 5: Velocity spectra normalized according to Olesen et al. (1984) for different stability classes. Stability classes s1 to s7 correspond to the following ranges of ζ: $0-0.05$, $0.05-0.15$, $0.15-0.35$, $0.35-0.65$, $0.65-1$, $1-1.5$, ≥ 1.5, respectively.

TKE Budget

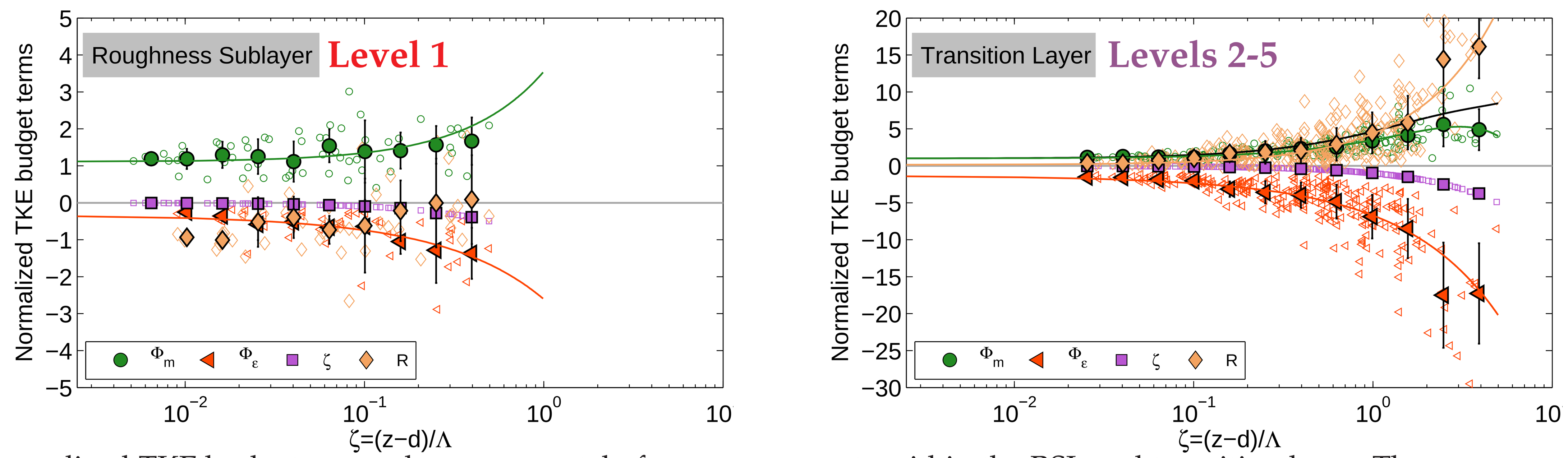


Figure 6: Normalized TKE budget terms shown separately for measurements within the RSL and transition layer. The green, orange and yellow curves represent the best fits of ϕ_m, ϕ_ε and residual term, respectively. The residual term is: $R = -\phi_m + \zeta + \phi_\varepsilon$.

- **The local equilibrium** between the production and destruction of TKE is **violated**.
- **Within the RSL:** shear production larger than buoyant destruction and dissipation of TKE $\Longrightarrow$ loss of energy for $\zeta \leq 0.1$. For $\zeta > 0.1$ the residual term changes sign and TKE balance is closed in the RSL.
- **In the transition layer:** the total local losses of TKE exceeds the local shear production $\Longrightarrow R > 0 \Longrightarrow$ gain of TKE.

Conclusion

- ϕ_ε at level 1 influenced by roughness elements, ϕ_ε at levels $2-5$: deviation from **local balance** in neutral conditions.
- Canopy scaling is successful; **wind variances** relevant for collapsing the spectra to a single curve.
- Despite the non-4/3 behavior, the Kansas spectral models can be used if ϕ_ε for vertical component is derived from S_w.
- The main reason for the **TKE non-closure** $\Longrightarrow$ in the transition layer: the non-local dynamics (Li et al., 2008) or inactive turbulence theory (Högström, 1990) and turbulent transport of TKE above vegetated canopies in the RSL.

References

[1] K. Babić, M. W. Rotach, and Z. B. Klaić. Evaluation of local similarity theory in the wintertime nocturnal boundary layer over heterogeneous surface. *Agric For Meteorol*, page In review, 2016.
[2] U. Högström. Analysis of turbulence structure in the surface layer with a modified similarity formulation for near neutral conditions. *J Atmos Sci*, 47:1949–1972, 1990.
[3] J. C. Kaimal and J. J. Finnigan. *Atmospheric boundary layer flows: their structure and measurements*. University Press, New York, 1994.
[4] J. C. Kaimal, J. C. Wyngaard, Y. Izumi, and O.R. Cote. Spectral characteristics of surface-layer turbulence. *Q J R Meteorol Soc*, 98:563–589, 1972.
[5] Xiangyi. Li, N. Zimmerman, and M. Princevac. Local imbalance of turbulent kinetic energy in the surface layer. *Boundary-Layer Meteorol*, 129:115–136, 2008.
[6] H.R. Olesen, S.E. Larsen, and J. Hojstrup. Modelling velocity spectra in the lower part of the planetary boundary layer. *Boundary-Layer Meteorol*, 29:285–312, 1984.
[7] J.C. Wyngaard and O.R. Cote. The budgets of turbulent kinetic energy and temperature variance in the atmospheric surface layer. *J Atmos Sci*, 28:190–201, 1971.

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