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Outer Length Scales in Nocturnal Stable Boundary Layers

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Abstract: Recently, Basu and Holstlag (2021) proposed a unified framework for describing outer length scales (OLS). By utilizing this framework, we document various characteristics of OLS in nocturnal boundary layers over the US Great Plains.
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Based on the variance and flux budget equations, Basu and Holtslag [1] derived closed-form solutions for outer length scale (OLS; denoted as L_X) and turbulent Prandtl number(Pr_t) for steady-state, stably stratified conditions. Specifically, they deduced:

$$L_X = \left(\frac{\sqrt{Pr_{t0}Pr_t}}{c_\theta}\right)\left(\frac{\sigma_\theta}{\Gamma}\right), \tag{1}$$

where the standard deviation of potential temperature is σ_θ. The gradient of mean potential temperature is represented by Γ. The turbulent Prandtl number for non-buoyant flows is denoted by Pr_{t0}; it is typically assumed to be equal to 0.85. The coefficient c_θ is approximately equal to 2. This newly proposed OLS (L_X) was shown to be related to several other well-known characteristic length scales of turbulence (e.g., Hunt length scale, Ellison length scale, Ozmidov length scale) for different asymptotic stability conditions (e.g., near-neutral, very stable). Furthermore, various analytical results of [1] were in close agreement with published observational and direct numerical simulation generated data (e.g., [2,3]).

According to the hypothesis by Kolmogorov–Obukhov–Corrsin, within the inertial-convective range (r), the second-order structure function of potential temperature (S_2^T) is written as:

$$S_2^T(r) = C_T^2 r^{2/3}, \tag{2}$$

where C_T^2 is the so-called temperature structure parameter. Based on the results from [1], Basu and Holtslag [4] further derived:

$$C_T^2 = \left(\frac{cPr_{t0}}{c_\theta^2}\right)\left(\frac{\sigma_\theta^2}{L_X^{2/3}}\right), \tag{3}$$

where the coefficient c is typically assumed to be around 3.2. By plugging in the typical values of the various coefficients, we can simplify Eq. (3) as follows:

$$C_T^2 = c_X\left(\frac{\sigma_\theta^2}{L_X^{2/3}}\right), \tag{4}$$

where, c_X is approximately equal to 0.68.

Under the assumptions of stationarity and homogeneity, the following relationship can be easily derived from the definition of S_2^T:

$$S_2^T(r) = 2\sigma_T^2\left[1 - C(r)\right], \tag{5}$$

where $C(r)$ is the autocorrelation function of potential temperature. By combining Eqs. (2), (4), and (5), one can arrive at:

$$C(r) = 1 - \left(\frac{c_X}{2}\right)\left(\frac{r}{L_X}\right)^{2/3}. \tag{6}$$

Thus, for $r = L_X$, the autocorrelation is approximately equal to 0.66. This simple finding is rather powerful as it will allow one to estimate L_X solely from measured temperature time series. Furthermore, with the estimated value of L_X, Eq. (4) can be subsequently used to predict the associated C_T^2 value.

During this presentation, we will demonstrate the prowess of the proposed approach by using measurement data from the CASES-99 field campaign [6]. For our analyses, data from sonic anemometers located at seven levels (5, 10, 20, 30, 40, 50, and 55 m) on a 60-m tower are considered. A few examples are shown in Fig. 1.

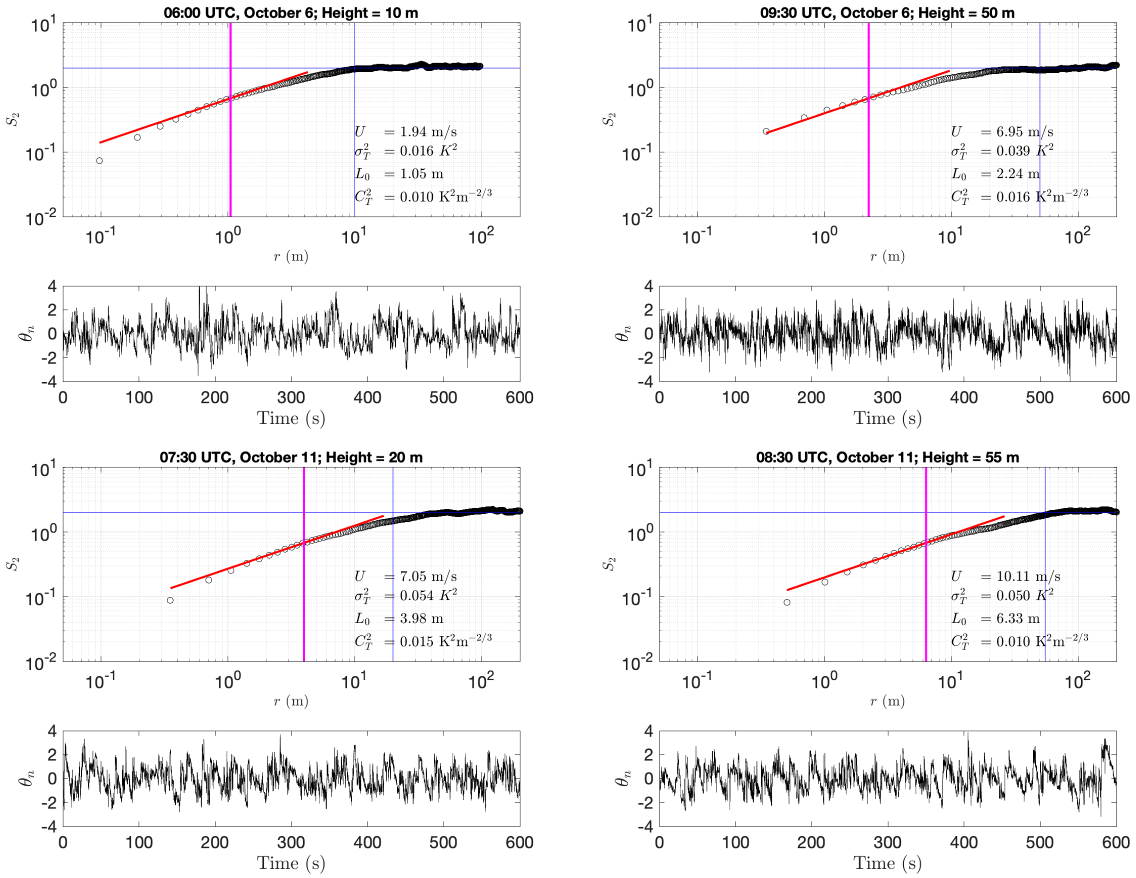

Fig. 1. Structure function analysis of four representative (normalized) temperature (θ_n) time series from the CASES-99 field campaign. Each time series is ten minutes long (sampling frequency of 20 Hz). The normalized series are shown at the bottom of the corresponding structure function plots. The black circles denote measured S_2^T values. The magenta colored lines on the structure function plots denote the estimated L_X values. The estimated C_T^2 values and other meteorological variables are also reported on these plots. From the estimated C_T^2 values, one can predict S_2^T values by making use of Eq. (2). These predicted S_2^T values are depicted on the structure function plots as red lines. The vertical blue lines simply denote $r = z$, where z is the height of the sonic anemometers. The horizontal blue lines represent $S_2^T = 2$. When the autocorrelation drops to zero, the ratio $\left(S_2^T/\sigma_\theta^2\right)$ approaches to 2 according to Eq. (5).

It is important to note that, more than fifty years ago, Fried [5] proposed a similar (not the same) formulation for OLS estimation from the autocorrelation function. In contrast to our analytical approach (utilizing the variance and flux budget equations), Fried's approach was based on heuristic arguments.

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