Integral turbulence characteristics over a clear woodland forest in northern Benin (West Africa)

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Abstract

The work of Monin and Obukhov has enabled a description of turbulent processes in the Atmospheric Boundary Layer using flux-variance similarity functions. These functions, also called Integral Turbulence Characteristics (ITC), are used to characterize the state of turbulence at all frequencies. However, due to the non-universality of ITC models, more investigations are necessary, especially in tropical regions where low wind conditions frequently occur. This study aims at investigating whether these normalized standard deviations obey the Monin-Obukhov Similarity Theory (MOST) above a forest site in the Sudanian climate, and at identifying the appropriate ITC models for this ecosystem. Data were collected from a 18m tower equipped with an Eddy Covariance system, above the clear forest at Bellefoungou's village, Northwest of Benin, West Africa. The turbulence intensity parameters calculated for five years and half, were analyzed according to wind speed, stability conditions and seasons. From their relationships with the stability parameter, data driven models were then obtained by the nonlinear least squares. The results showed that, all similarity functions follow MOST with a 1/3 power law whatever the stratification of the atmosphere during all the seasons excepted the temperature which had a parabolic shape in near neutral condition ($-0.05 < \zeta < 0.1$). A seasonal dependence of all ITCs was evidenced under stable conditions. Indeed, roughness length and strong winds which dominating especially in the dry season favored more efficient turbulent exchange at the site. We also showed that the heat transfer is relatively more efficient than H_2O transfer under both stability conditions. The established temperature and CO_2 similarity models are found to be closer, and for some given stratification conditions, to those already existing in literature. But a noteworthy finding is that the models often used to assign a quality criterion to turbulent fluxes showed an overestimation relatively to those established 'locally' for u and w through all atmospheric stratification.

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Introduction

Understanding atmospheric turbulence is essential for evaluation of weather forecasting and atmospheric models (Lee et al., 2020) and the study of pollutant dispersion (Cohan et al., 2011) in the Atmospheric Boundary Layer (ABL). According the **Monin-Obukhov Similarity Theory** (**MOST**), the Integral Turbulence Characteristics (ITC), are used to characterize the state of turbulence at all frequencies (Foken, 2017). These ITC are useful to assess the quality of eddy covariance flux measurements (Foken et al., 2012), to estimate the fluxes by the flux-variance method (Hsieh et al., 2008). However, due to the non-universality of ITC models, more investigations are necessary, especially in tropical regions where low wind conditions frequently occur. In this study realized above a forest site in Benin, we have (1) analyzed the dependence of the ITC for different seasons (dry and wet) and transitional phases (drying, moistening); (2) examined whether these relationships follow or not the MOST and build data-driven ITC models and (3) investigated the efficiency of turbulent transfer at the study site.

Theoretical background

Flux-variance similarity function

The normalized standard deviations of wind speed components ($\sigma_{u,v,w}/u_*$) and atmospheric scalars ($\sigma_{T,q,CO2}/x_*$) are supposed to be functions of the atmospheric stability parameter (ζ). These functions $\varphi_i(\zeta)$ are called flux-variance similarity functions or integral turbulence characteristics and are often defined as follows:

$$\varphi_i(\zeta) = a_i(1 \pm b_i\,\zeta)^{\pm c_i}$$

$$\zeta = \frac{z-d}{L} \quad with \quad L = -\frac{u_*^3\,\bar{T}}{\kappa g\,\overline{w'T'}}$$

$$u_* = \sqrt{\left|-\overline{u'w'}\right|} \quad and \quad x_* = -\frac{\overline{w'x'}}{u_*}$$

The coefficients a_i, b_i and c_i are explicitly determined from the dataset herein in this study

Turbulent transfer efficiency

$$r_{wx} = \frac{\overline{w'x'}}{\sigma_w \sigma_x} \quad with \quad x = u, T, q, CO_2$$

$$\frac{r_{wT}}{r_{wx}} = \frac{\sigma_x}{x_*}\Big/\frac{\sigma_T}{T_*} \quad with \quad x = u, q, CO_2$$

r_{wx} is the turbulent correlation coefficients

Site and instrumentation

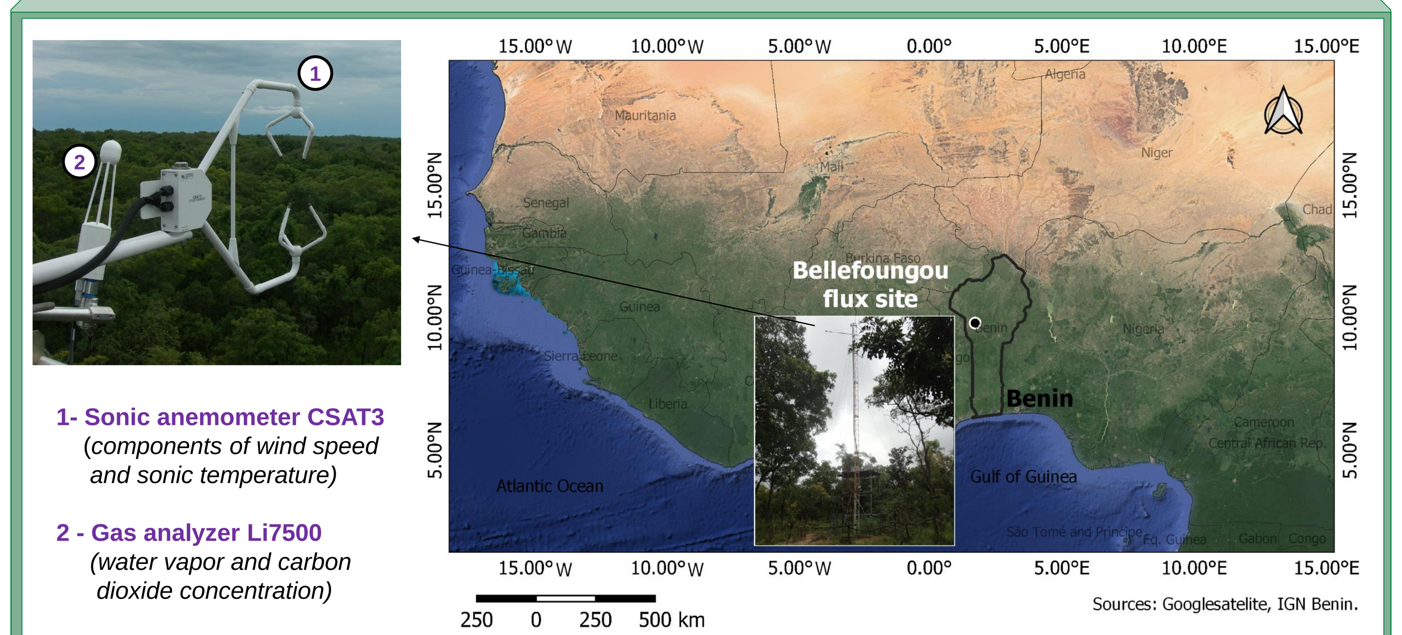

Fig.1: Geographical location of the Bellefoungou forest site

The data given in this study cover five and a half years of continuous measurements from 28th June 2008 to 31st December 2013.

Results

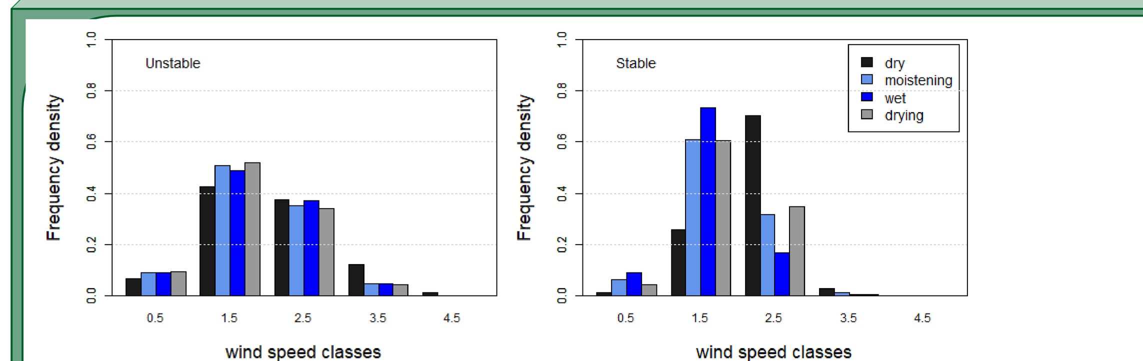

Fig.2: Wind speed frequency density histogram.

During stable conditions, higher occurrences in higher wind speeds (2-3m.s[-1]) appeared in the dry season while the remaining seasons were marked by more lower wind speeds (<2m.s[-1]).

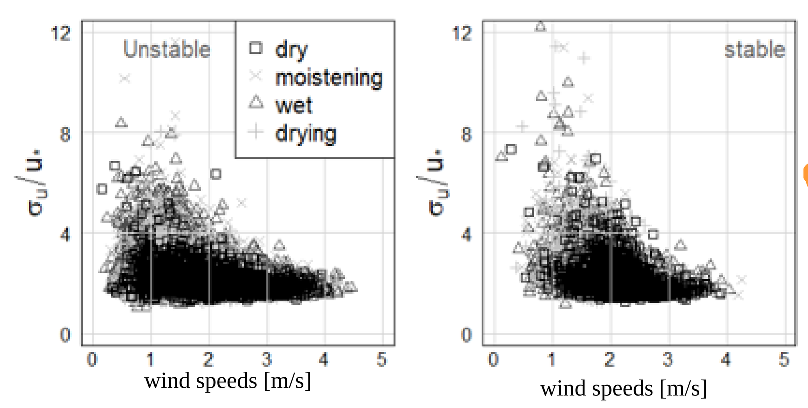

Fig.3: Relationship between the normalized standard deviations of wind speed components and wind speeds.

The ITC decrease when the wind speed increases, mainly in stable atmospheric conditions

ITC models and their seasonal variability

All integral turbulence characteristics obey MOST except that of temperature near neutral stability.

The integral turbulence characteristics varied seasonally under stable conditions.

A mismatch between the obtained models and those of literature is evidenced.

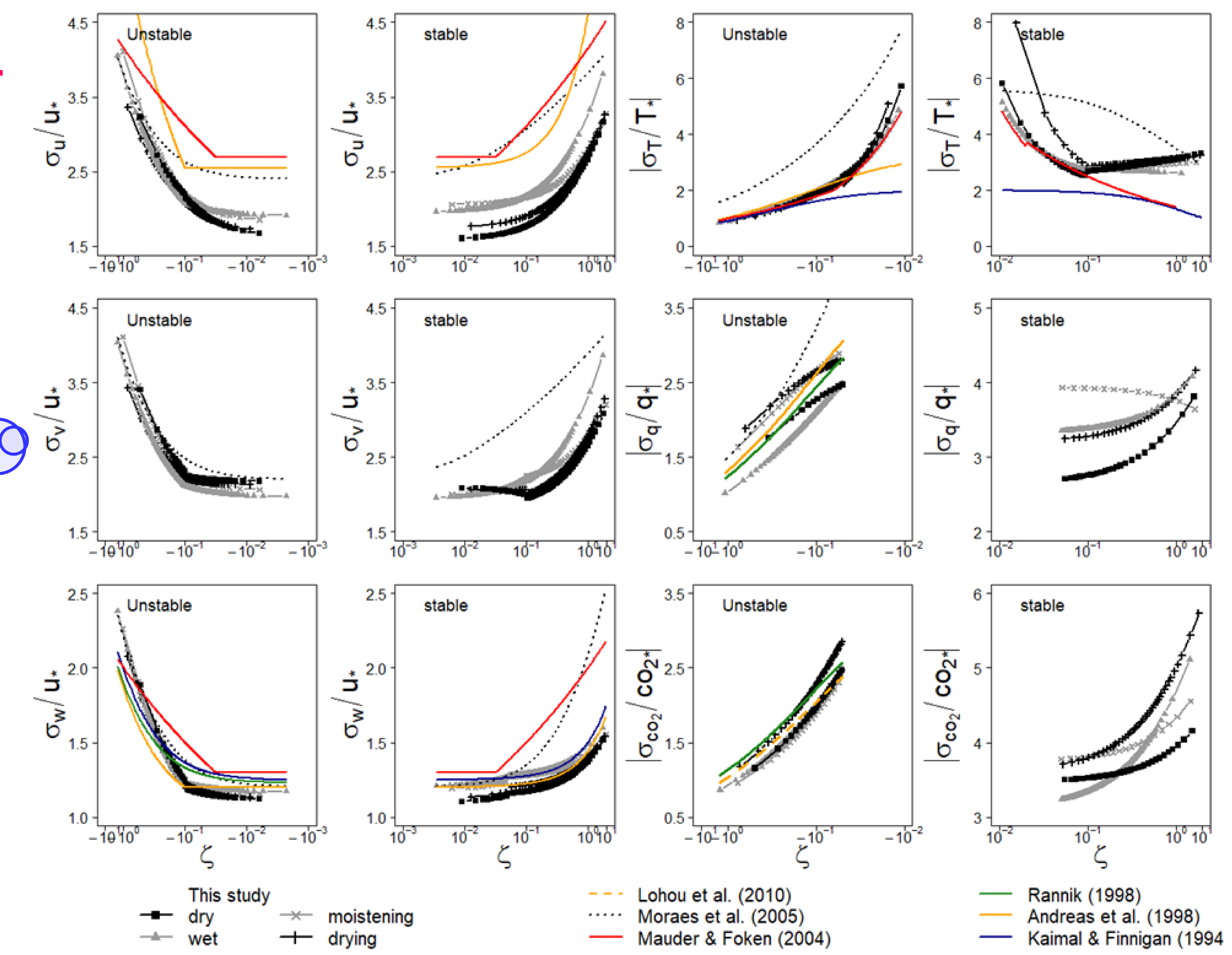

Fig.4: The fitted curves of the ITC obtained over the Bellefoungou site during dry, wet, moistening, and drying seasons. Some the literature models are also represent.

Turbulent transfer efficiency over the site

Turbulent exchanges are more efficient in the dry season compared to the wet season under stable condition.

Heat and CO_2 transfers are similar under unstable conditions.

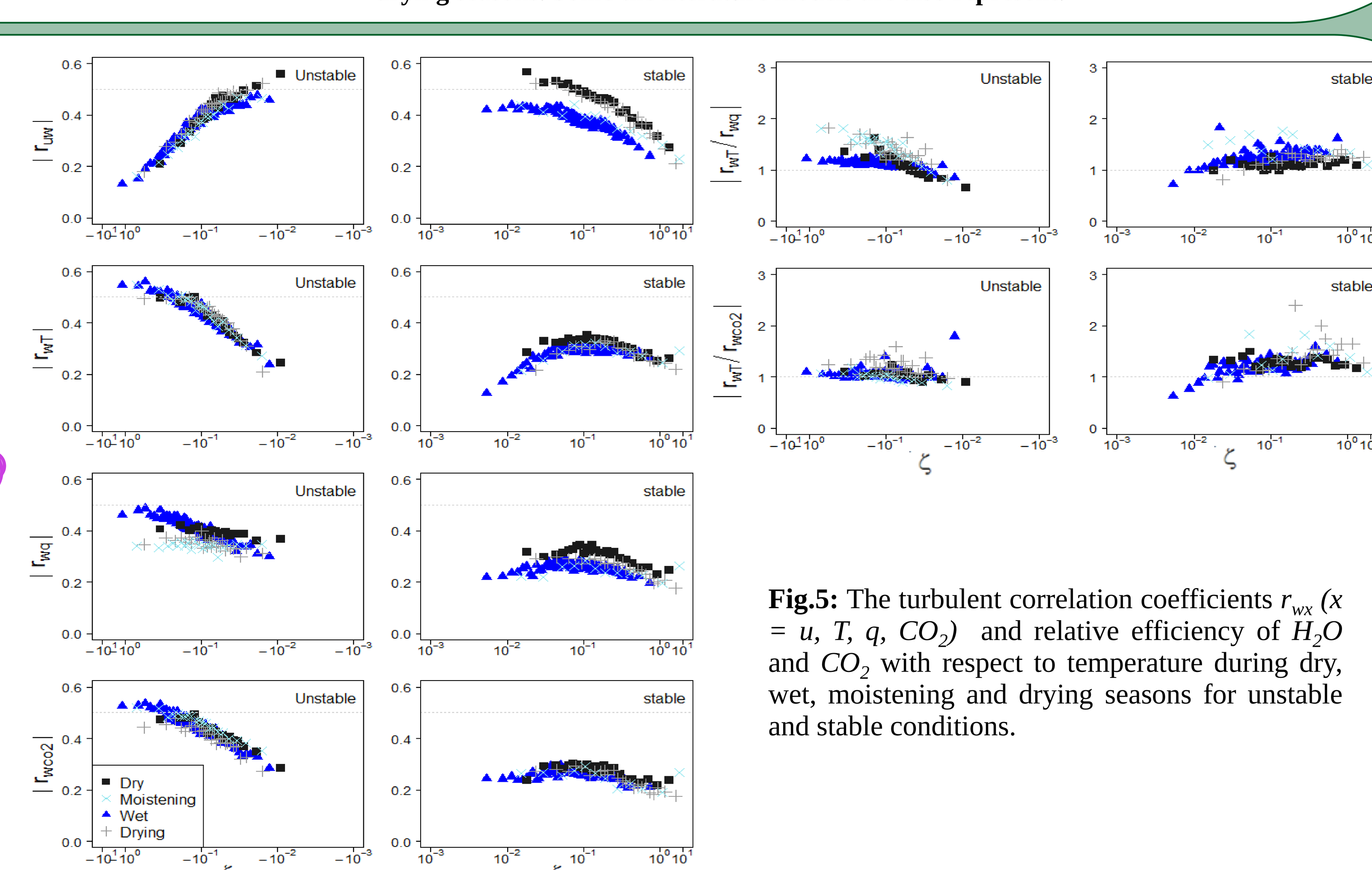

Fig.5: The turbulent correlation coefficients r_{wx} ($x = u, T, q, CO_2$) and relative efficiency of H_2O and CO_2 with respect to temperature during dry, wet, moistening and drying seasons for unstable and stable conditions.

Discussion

The results showed a seasonal dependence of ITC. this seasonal variability could be related to both the wind speed intensities and the roughness length, especially in dry season. These favor the wind shear leading probably to more dynamical turbulence. The similarity models established for temperature and CO_2 are closer, and for some given stratification conditions, to those already existing in literature. But a noteworthy finding is that the models often used to assign a quality criterion to turbulent fluxes (Foken and Wichura, 1996) showed an overestimation relatively to those established 'locally' for u and w through all atmospheric stratification.

Conclusion

Although some ITC are seasonally dependent, especially under stable conditions, all ITC respect MOST whatever the stratification of the atmosphere, except the temperature in near neutrality. The novelty of this study, the first in the whole West African region above such an ecosystem, lies in the fact that data-driven models have been established for all wind speed components and scalars during all stability regimes.

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