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Abstract: In this manuscript, some micrometeorological characteristics of the Pantanal are presented. This region, one of the greatest wetlands in the world, is located in the central western part of South America. It has very peculiar environmental and ecological characteristics, a great biodiversity and an irregular hydrological cycle, which often presents floods during the wet season and droughts and fires during the dry season. The experimental data were collected in a meteorological tower during the Interdisciplinary Pantanal Experiment (IPE), on April-May 1998. This was a transition period between the wet and the dry season, which a shallow water layer was present at several parts of the experimental field, even around the 25m-height meteorological tower. The surface energy budget components associated with the existence of the shallow water layer, its diurnal variability and some turbulent variables related to the surface-atmosphere turbulent exchange processes were investigated. Eddy-correlation and variance methods have been used to estimate turbulent fluxes and to study the validity of the Monin-Obukhov similarity theory for the Pantanal region. A mixed layer slab model has been used to estimate the height of the turbulent mixing-layer and to provide useful information to test the validity of general relationships concerning horizontal wind velocity variances above Pantanal. In general, the dimensionless relationships between turbulent variables and scaling parameters agree well with the ones found in the literature. Some aspects regarding the heat storage in the shallow water layer present interesting information about its role in the surface-atmosphere energy exchanges processes along the day.

Rio de Janeiro, December 05th, 2007

Dr. Monique Leclerc
Associate Editor
Agricultural and Forest Meteorology

Dear Dr. Leclerc

We acknowledge receipt of your journal the request of a second revision of our manuscript entitled: *"Atmospheric surface layer characteristics of turbulence above the Pantanal wetland regarding the similarity theory"*, for which we thank you.

We appreciate again the useful comments and suggestions made by the Reviewers. We believe that these suggestions have permitted the improvement of our manuscript.

We are fortunately able to in a position to send you the proper responses, in the attachment. And we would like to inform you that the reviewed manuscript was electronically resubmitted to the journal *Agricultural and Forest Meteorology*.

If you please require any further information, do not hesitate to contact us.

Thank you in advance for your consideration.

Yours sincerely,

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Answer to the Reviewers

We want to thank to the Reviewers for the second revision. We appreciate very well the useful suggestions. The answers are enclosed below.

Questions

1) *I wonder if the near jump in the model for* r_{uw} *near* $\zeta = -1$ *(Fig. 8b) is really supported by the data?*

A smooth jump has been observed in the data, which could be adjusted by a sigmoidal function with a relatively small width. This type of fitting is based on the idea of that the correlation coefficients, r_{wT} and r_{uw}, are nearly constants along some defined intervals of ζ (according to Table 2 of Kaimal et al., 1972).

The correlation coefficients can be viewed as a measure of the overall efficiency of the transfer and varies between zero (no correlation) and 1 (optimally efficient transfer) (Roth and Oke, 1995). In accord with these authors the relative transfer efficiencies are given by:

$$-\frac{r_{wT}}{r_{uw}} = -\frac{u_* T_*}{\sigma_w \sigma_T} \cdot \frac{\sigma_u \sigma_T}{u_* u_*} = \frac{\sigma_u / u_*}{\sigma_T / T_*} = \frac{\phi_U}{\phi_T} \quad (1)$$

where the universal function for the Pantanal are:

$$\left.\begin{aligned} \phi_U(\zeta) &= (5.23 - 7.94\zeta)^{1/3} \\ \phi_T(\zeta) &= (0.02 - 0.65\zeta)^{-1/3} \end{aligned}\right\} \quad \text{for} \quad \zeta < 0$$

$$\left.\begin{aligned} \phi_U(\zeta) &= (1.74 + 0.36\zeta) \\ \phi_T(\zeta) &= 2.64 \end{aligned}\right\} \quad \text{for} \quad \zeta > 0$$

To verify the sigmoidal fits, the modeled ratio $-r_{wT}/r_{uw}$ was compared with the observed ratio $-r_{wT}/r_{uw}$. Notice that the previously proposed fits in the manuscript was not adequate, as indicated by the Reviewer, because the data seem not to support a jump of first order. For this reason, a revision of the sigmoidal fits was considered below:

$$r_{wT}\left(\zeta\right)=0.81\left[\frac{1}{1+e^{5(\zeta+0.10)}}\right]-0.30 \qquad \text{for} \quad -3\leq\zeta\leq2 \qquad (2a)$$

$$r_{uw}\left(\zeta\right)=0.18\left[\frac{1}{1+e^{5(\zeta+1.25)}}\right]-0.32 \qquad \text{for} \quad -3\leq\zeta\leq2 \qquad (2b)$$

The Figure 1 shows that the new sigmoidal fits are able to adjust the data along the range $-3\leq\zeta\leq2$. The new curves are limited by the standard deviation bars, and $r_{wT}\left(\zeta\right)=0$ at $\zeta=0$.

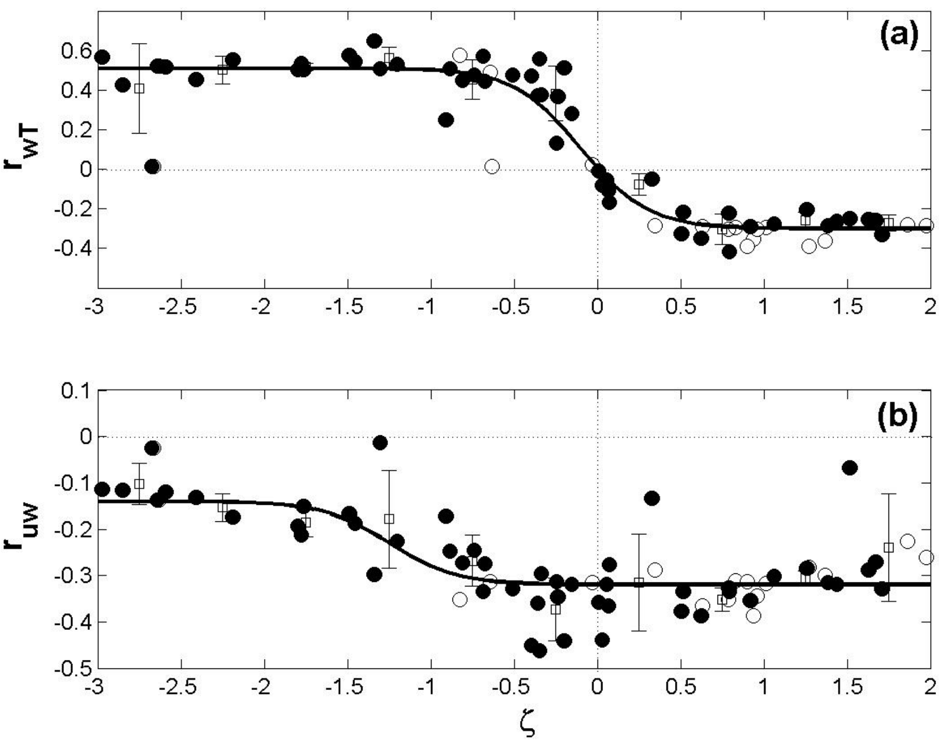

Fig. 1 – Correlation coefficients with the standard deviation bars for: a) heat flux r_{wT} ; b) momentum flux r_{uw}. The solid lines represent the fitting curves for Pantanal (Eqs. 2a and 2b). The solid and open circles represent the stationary and non-stationary data, respectively.

To verify the fits, the modeled ratio between the new sigmoidal curves (Eqs. 2a and 2b) is compared with the observed ratio and with the predicted ratio by MOST (Eq. 1). The results are shown in Fig. 2.

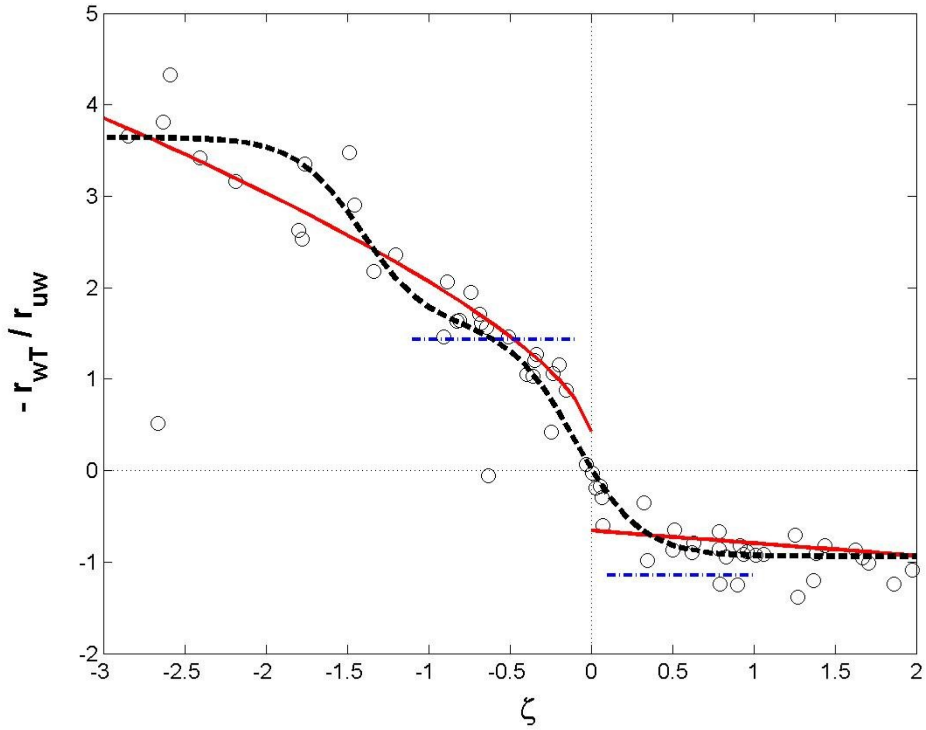

Fig. 2 – Ratio of correlation coefficients versus stability for heat and momentum (open circles). The black dashed line is the modeled ratio (Eqs. 2a and 2b). The red solid lines are the MOST predictions (Eq. 1). The blue dashed-dot lines are the values proposed by Kaimal and Finnigan (1994).

Notice that the observed ratio $-r_{wT}/r_{uw}$ is in agreement with both of the modeled ratio (Eqs. 2a and 2b) and MOST predictions (Eq. 1). The values proposed by Kaimal and Finnigan (1994) are included for comparison and shows significant differences in relation to the observed ratio $-r_{wT}/r_{uw}$, providing only a rough approximation to the true behavior in the limited range $-1 \le \zeta \le 1$.

2) *There are still a number of small English things although the paper is very clearly written.*

All the suggested English corrections were implemented in the text.

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ATMOSPHERIC SURFACE LAYER CHARACTERISTICS OF TURBULENCE ABOVE THE PANTANAL WETLAND REGARDING THE SIMILARITY THEORY

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ATMOSPHERIC SURFACE LAYER CHARACTERISTICS OF TURBULENCE ABOVE THE PANTANAL WETLAND REGARDING THE SIMILARITY THEORY

ABSTRACT

In this manuscript, some micrometeorological characteristics of the Pantanal are presented. This region, one of the greatest wetlands in the world, is located in the central western part of South America. It has very peculiar environmental and ecological characteristics, a great biodiversity and an irregular hydrological cycle, which often presents floods during the wet season and droughts and fires during the dry season. The experimental data were collected in a meteorological tower during the Interdisciplinary Pantanal Experiment (IPE), on April-May 1998. This was a transition period between the wet and the dry season, which a shallow water layer was present at several parts of the experimental field, even around the 25m-height meteorological tower. The surface energy budget components associated with the existence of the shallow water layer, its diurnal variability and some turbulent variables related to the surface-atmosphere turbulent exchange processes were investigated. Eddy-correlation and variance methods have been used to estimate turbulent fluxes and to study the validity of the Monin-Obukhov similarity theory for the Pantanal region. A mixed layer slab model has been used to estimate the height of the turbulent mixing-layer and to provide useful information to test the validity of general relationships concerning horizontal wind velocity variances above Pantanal. In general, the dimensionless relationships between turbulent variables and scaling parameters agree well with the ones found in the literature. Some aspects regarding the heat storage in the shallow water layer present interesting information about its role in the surface-atmosphere energy exchanges processes along the day.

Keywords: Atmospheric Surface Layer; Heterogeneous surface; Pantanal wetland; Surface energy budget; Monin-Obukhov similarity theory.

1. Introduction

The turbulence processes in the atmospheric surface layer (SL) play a major role in the transport of momentum, sensible and latent heat in the atmosphere (Monin and Yaglom, 1971). Particularly, in the SL the turbulent fluxes are essencial for accoplishing atmospheric surface interactions. The SL turbulent structures on horizontally homogeneous surfaces are yet well known (Kaimal and Wyngaard, 1990). The influences of surface heterogeneities have been intensively studied, resulting in proper formulations (Garratt, 1980; Raupach *et al.*, 1996; Jacobs *et al.*, 1997; Andreas *et al.*, 1998; von Randow *et al.*, 2006).

The goal of this work is verifying the validation of the Monin-Obukhov similarity theory (MOST) on the Pantanal wetland, a very large heterogeneous swamp area in central-western Brazil, during a transition period from wet to dry season. Additionally, the surface energy budget and others SL turbulent parameters were computed, discussed and compared with some other research results over complex and flooded terrain. Such pieces of information are also very useful for modeling processes concerning parameterizations above heterogeneous surface (Garratt, 1992).

Even though Pantanal is considered a very important ecosystem, few meteorological investigations have been realized in this region yet. The Interdisciplinary Pantanal Experiment (IPE-1) was the first micrometeorological field campaign carried out in Pantanal, addressed to provide an adequate characterization of the SL structure over the wetland surface, and to obtain useful data for a better understanding of the surface energy budget components associated with the shallow water layer, and some meteorological variables characteristic of the surface-atmosphere turbulent exchange processes.

The Pantanal ecosystem is one of the larger wetland in the world with near 160,000 km^2 (Junk and Cunha, 2005) and UNESCO World Heritage Site. It is located in the center of South America and 85% of its region belongs to the Brazilian territory, between the states of Mato Grosso and Mato Grosso do Sul. Its boundaries are the Amazonian rain forest on the North, and the Brazilian central plateau on the East. In this region, there is a significant area of tropical savanna grasslands of which Pantanal is an immense sedimentary prairie characterized by a seasonal flooding pattern and peculiar fetch conditions. The climate of Pantanal presents a quasi-regular hydrological cycle with some inter-annual oscillation, which often presents floods during the wet season (November-March), and natural and anthropogenic fires during the dry season (July-October). The precipitation oscillates between 1000-1500 mm year^{-1} and almost 80% of this precipitation occurs in the summer season, between the months of November and March (Hamilton *et al.*, 1996). The vegetation is typical of an open arboreal savanna region, composed by trees, called Paratudal, rooted floating plants or free floating plants. There are also grass and natural pasture (Por, 1995).

This manuscript is divided in five sections: section two presents the theoretical background; section three describes the experimental site and the data quality control procedure; section four discusses the results; and section five summarizes the conclusions.

2. Theoretical elements

The turbulence characteristics in the SL can be described by the universal laws of the MOST under some different stability conditions (Panofsky and Dutton, 1984). Over a horizontally homogeneous surface and under quasi-stationary conditions, the scaling turbulent parameters for momentum, temperature, specific humidity and height can be written as:

$$u_* = \left[\left(\overline{u'w'} \right)_0^2 + \left(\overline{v'w'} \right)_0^2 \right]^{1/4} \tag{1a}$$

$$T_* = -\left(\overline{w'T'} \right)_0 \Big/ u_* \tag{1b}$$

$$q_* = -\left(\overline{w'q'} \right)_0 \Big/ u_* \tag{1c}$$

$$L = -u_*^3 \Big/ \kappa g \left(\frac{\overline{w'T'}}{T_0} + 0.61 \overline{w'q'} \right) \tag{1d}$$

where u', v' and w' are the fluctuations of the wind velocity components; T' and q' are the fluctuations of temperature and specific humidity, respectively; u_* is the velocity scale; T_* and q_* are the temperature and humidity turbulent characteristic scales, respectively; L is the Obukhov length scale; g is the gravity acceleration; and κ is the von Karmán constant $(\kappa = 0.4)$ (Högström, 1996).

For many SL applications, it is necessary to have information about the characteristics of the vertical profiles and turbulent fluctuations of the micrometeorological variables (Sorbjan, 1986; Viswanadham *et al.*, 1990; Garratt, 1992).

The MOST predicts that the turbulent characteristics near the ground are related to the universal functions, ϕ, through of the stability parameter $\zeta = z/L$, where z is the height over the ground. Therefore, the dimensionless standard deviations of the wind velocity components $\sigma_{u,v,w}/u_*$ and temperature σ_T/T_* should be obtained (Sorbjan, 1989; Kader and Yaglom, 1990; Högström, 1996) as:

$$\phi_i(\zeta) = \frac{\sigma_i}{u_*} = \begin{cases} (a_i + b_i \zeta)^{1/3} & \text{for } \zeta < 0 \\ (c_i + d_i \zeta) & \text{for } \zeta > 0 \end{cases} \tag{2a}$$

$$\phi_T(\zeta) = \frac{\sigma_T}{T_*} = \begin{cases} (a_T + b_T\zeta)^{-1/3} & \text{for} \quad \zeta < 0 \\ (c_T + d_T\zeta)^{-1} & \text{for} \quad \zeta > 0 \end{cases} \qquad (2b)$$

where $a_{i,T}$, $b_{i,T}$, $c_{i,T}$ and $d_{i,T}$ are universal constants, with $i = (u, v, w)$. In this study, the appropriate length scale used to compute ζ is $(z - d)$, the effective height above the zero-plane displacement, d. The universal constants in the Eqs. (2a and 2b) are generally determined by field experiments (Sorbjan, 1986; Kader and Yaglom, 1990; Högström, 1996; Khanna and Brasseur, 1997; Andreas *et al.*, 1998) and here, they have been obtained by least square method. There are still some disagreements concerning the application of the MOST for data measured over heterogeneous surfaces, especially over forests and water paths (Thom *et al.*, 1975; Garratt, 1980; Raupach *et al.*, 1996; Sun *et al.*, 1996; Marht, 1999).

3. Experimental site and data analysis

The IPE-1 was conducted during the transition period between the wet and the dry seasons, i.e. on April and May of 1998. The experimental site is located in the southern region of Pantanal wetland (19^{o}34' S, 57^{o}01' W, altitude 80 m) in Mato Grosso do Sul State, Brazil. A 21 m-height instrumented tower, with a supplementary 4m mast erected at its end, was built on a vegetated terrain covered by a shallow water layer with 7 to 15 cm-depth.

The turbulent measurements at the level of 25 m for the wind velocity components (u', v', w') and temperature (T') were acquired at a sampling rate of 21Hz (Gill-Solent sonic anemometer), for a period of six rain-free days. The slow response data of mean wind velocity (U) (Vector Instruments anemometer), air temperature (T) and specific humidity (q) (Campbell psycrometer), were measured at 6 different levels (2.0, 3.75, 8.1, 9.75, 15.7 and 21.5 meters). The net radiation (R_n) (REBS net radiometer) was measured at 4 and 20.4 meters above the surface. The soil temperature (T_s) (Campbell thermistor) and the soil heat flux (G_{out}) (REBS fluxmeter) were measured at 3 different depths into the ground (-1, -2 and -10 cm), i.e. below the shallow water layer. All the slow response measurements were recorded at a sampling rate of 10 minutes.

The data quality control procedure of Vickers and Mahrt (1997) was applied to remove spikes and missing portions of the turbulent measurements. Many phenomena can lead to non-stationary series such as diurnal trends, mesoscale circulations, and surface heterogeneity (Mahrt *et al.*, 1994; Sun *et al.*, 1996; von Randow *et al.*, 2002). They can affect the surface fluxes estimate by eddy-correlation (EC). The non-stationarity of the Pantanal data series was identified by the methodology of Mahrt (1998). The result indicates that 35% of the records are non-stationary, mainly during the late afternoon and at night. However, the nonstationary data seems not increase significantly the scattering of the standard deviation and correlation coefficients in the range $-3 \le \zeta \le 2$, as will be showed in the next section.

The low-pass filter based on wavelets transforms (Daubechies, 1992) was applied to the turbulent data for removing the very low frequency fluctuations (cutoff $f \le 2\times10^{-3}\,Hz$), after the coordinate system has been aligned with the mean wind direction. On the other hand, a recursive digital filter (Otnes and Enochson, 1972) was applied in the slow response measurements to assure greater accuracy in the U, T and q vertical gradient calculations.

The temporal evolution of micrometeorological parameters in SL was obtained for every τ = 60 minutes data window. According to Shuttleworth *et al.* (1984), the choice of the appropriate τ value takes in account two conditions: (a) it should be long enough to include most of the low frequency contributions in the co-spectra between vertical wind speed and the other fluctuations meteorological variables; (b) at the same time, very large values of τ could make the flux susceptible of contamination by low frequency correlations associated with mesoscale motions, or due instrument-generated spurious correlations.

In IPE-1, the average wind velocity was smaller than 4 m s^{-1}, the virtual temperature was between 13.5 ^oC and 37.4 ^oC, and the specific humidity was between $9\ g\,kg^{-1}$ and $28.5\ g\,kg^{-1}$.

4. Analyses and results

The SL turbulent flow above very rough surfaces is dynamically influenced by the average roughness as well as by individual elements present on the surface. It has very complex characteristics compared with the turbulent flow above smooth and horizontally homogeneous surfaces (Garratt, 1980; Viswanadham *et al.*, 1990; Raupach *et al.*, 1996; von Randow *et al.*, 2002).

In general, to express the action of a complex surface drag in the atmospheric flow, two aerodynamic parameters are used: the zero-plane displacement d and the roughness length z_0 (Thom *et al.*, 1975). The former indicates the vertical level where the mean wind, extrapolated from above, approaches zero, and should be considered the level of action of the surface drag by the main roughness elements (Thom, 1975). According to Kaimal and Finnigan (1994), the value of d is often estimated as a fraction of the canopy layer height, $h_c\ (d \approx 0.75\,h_c)$.

The accurate determination of d requires adequate fetch conditions and instrumental measurements at heights greater than h_c (Wieringa, 1993). De Bruin and Verhoef (1997) suggested an alternative method to estimate d through the similarity relationships associated with the estimated standard deviation of the vertical wind velocity (σ_w) under free convection condition, which has been used in this investigation. This procedure allows a proper determination of d with fast response w' and T' data measured only at one height.

In this study was considered the following criterion to free convection definition, $\zeta < -2$, which is consistent with the preposition by Kader and Yaglom (1990). Considering only the values of d found in the range limited to two standard deviation from the average, d is equal to 4.96 ± 0.56 for the Pantanal. This value is similar to the value could be obtained with the Kaimal and Finnigan (1994) simplified methodology$(d \approx 0.75\, h_c \approx 5\, m)$.

4.1 Surface energy budget

The surface energy budget (SEB) is associated with the SL turbulent structure. Therefore, the shallow water layer (SWL) on the Pantanal area must be considered. Following Oke (1987) and Jacobs *et al*. (1997), the SEB on the interface of the SWL may be written as (Fig. 1):

$$R_n = H + LE + G_{in} \tag{3}$$

where H is the sensible heat flux; LE is the latent heat flux; and G_{in} is the heat flux into SWL. H is estimated by the EC method; $G_{in} \approx R_n - H - LE$ is computed as a residual term of the SEB (Eq. 3); and G_{out} is the measured soil flux just below the SWL (Fig. 1). The SWL energy storage, ΔS, is estimated as $\Delta S \approx |G_{in}| - |G_{out}|$. Since q' measurements were not available during the IPE-1 experimental campaign, LE has been obtained indirectly by the Bowen ratio energy balance method, as suggested by Liu and Foken (2001).

The Bowen ratio β was estimated using the slow response measurements of T and q, according to the equation below:

$$\beta = \frac{c_p}{L_v}\frac{\Delta\overline{T}}{\Delta\overline{q}} \quad (4)$$

where $\Delta\overline{T}$ and $\Delta\overline{q}$ are, respectively, the mean differences of temperature and specific humidity, respectively, at two vertical levels near to ground; c_p is the specific heat of air at constant pressure; and L_v is the latent heat of vaporization for water.

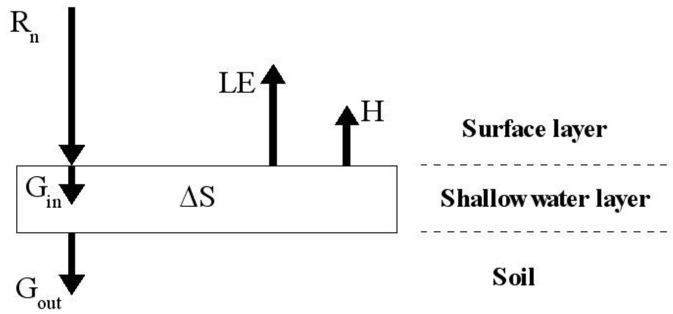

Figure 1 – Schematic overview of the shallow water layer energy budget under diurnal conditions.

The temporal evolution of the SEB components is presented in the Fig. 2. The focus of our analysis is the daytime partition of the energy. On average, for Pantanal, the mean β is near 0.36 ± 0.01, which is lower than the mean value of 0.4 estimated above the Amazonian rain forest (von Randow *et al.*, 2002). This indicates the great energy availability for water evaporation on the Pantanal surface.

The SWL contains a lot of embedded vegetation. The presence of vegetation should imply a specific radiation transfer through the depth of the water body and a particular energy budget. During the first hours in the morning, the surface of the SWL quickly warms due to the absorption of the incoming solar radiation, allowing the occurrence of a mean SWL temperature greater than in the soil surface bellow $(\Delta S > 0)$. In the next hours, the SWL is able to transfer heat to the ground (Fig. 2). Thus, ΔS remains negative until the end of the afternoon.

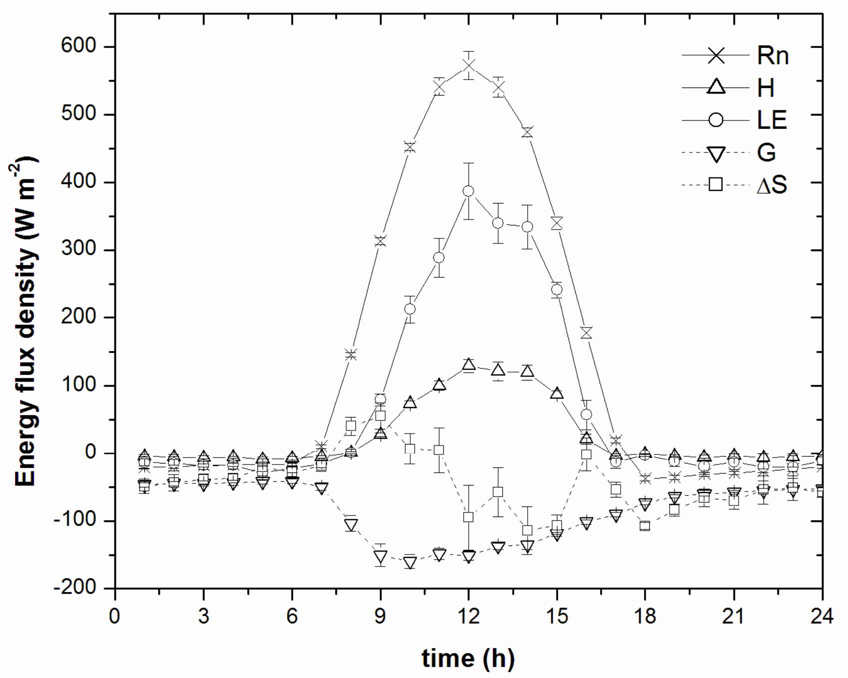

Figure 2 – Temporal evolution of the surface energy budget mean components for the Pantanal region with the respective standard deviations bars.

In order to introduce useful information for discussion, we will consider Jacobs *et al.* (1997) reasoning, one of the few available environmental results regarding the energy budget in a SWL. Comparatively, the SWL depth presented by Jacobs *et al.* (1997) is thicker than the one in Pantanal. Consequently, our SWL warms faster and stores less heat than theirs. The picks and valleys, notable on the ΔS line, are probably associated to large term differences used to compute the residue of Eq. (3).

Another peculiar characteristic of the SEB in Pantanal is that the SWL provides a thermal insulation of the ground. Hence, the heat soil flux G_{out} is always downwards, even during the night.

These behaviors are considered a regional characteristic of Pantanal area in the wet season from a qualitative point of view. In the dry season, the SWL completely evaporates and the soil is exposed to the solar radiation heating, resulting in another distinct energy budget that will be the subject of new studies. Despite the short period of the experimental campaign the intention of this work was describing the dynamics and thermodynamics features usually found in the Pantanal SL, and establishing a methodology useful to the data analysis.

4.2 Applicability of Monin-Obukhov Similarity Theory

a) Standard deviation of temperature

The applicability of the MOST is verified by performing an analysis of H estimates, considering both the EC $\left(H_{eddy}\right)$ and the variance $\left(H_{var}\right)$ methods. In the literature, Lloyd *et al.* (1991) have shown that the variance method reproduces very well the H estimates by the EC method for four different surface types. Katul *et al.* (1995) made a review about the variance method above uniform and non-uniform terrains. Other authors also have used this technique and obtained good results for several distinct land surfaces (Albertson *et al.*, 1995; De Bruin and Hartogensis, 2005; von Randow *et al.*, 2006).

The variance method allows the H estimate once provided the σ_T measurements, based on the MOST (Katul *et al.*, 1995):

$$H_{var} = \rho c_p \left(\frac{\sigma_T}{0.97} \right)^{3/2} \left(\frac{\kappa g z}{T} \right)^{1/2} \quad \text{for} \quad \zeta < 0 \tag{5}$$

Before applying the variance method, the relationship between σ_T / T_* and ζ has been computed (Fig. 3). Therefore, the universal function $\phi_T(\zeta)$ (Eq. 2b) has been obtained by least square method. The fitting curve resulting for the Pantanal data under unstable conditions is:

$$\phi_T(\zeta) = (0.02 - 0.65\zeta)^{-1/3} \quad \text{for} \quad \zeta < 0 \tag{6}$$

Figure (3) shows the associated fitting of $\phi_T(\zeta)$ that is comparable to the proposed by Albertson *et al.* (1995) and Andreas *et al.* (1998). Under free convection condition ($\zeta < -2$), $\phi_T(\zeta)$ tends to the asymptotic behavior $\zeta^{-1/3}$ as $\zeta \to -\infty$, as predicted by Wyngaard *et al*. (1971).

The normalized standard deviation σ_T / T_*, under neutral condition, shows a large scattering because σ_T and T_* are both varying close to zero, and consequently the experimental accuracy is expected to be very low (Pahlow *et al.*, 2001; De Bruin and Hartogensis, 2005). Another aspect that contributes to this the larger scattering is the temperature fluctuations associated to the thermal heterogeneities, which can exist even if the H is almost zero in a mean sense (Kader and Yaglom, 1990; Tsvang *et al.*, 1998).

Under stable condition, even with the scattering of the points (Fig. 3), σ_T / T_* tends asymptotically to 2.64 ± 0.56, which agrees with the empirical values 2.9 and 3.0 proposed by De Bruin *et al.* (1993) and Pahlow *et al.* (2001), respectively.

Mahrt (1999) provides one complete list of problems found under stable condition. Particularly, the evaluation of the MOST should contain a significant contribution of the self-correlation (Mahrt *et al.*, 1998; Klipp and Mahrt, 2004; Baas *et al.*, 2006) and there is enormous difficult for achieving the universal fit or parameterization. The self-correlation problem will be discussed in details to the standard deviation of wind velocity components in subsection b.

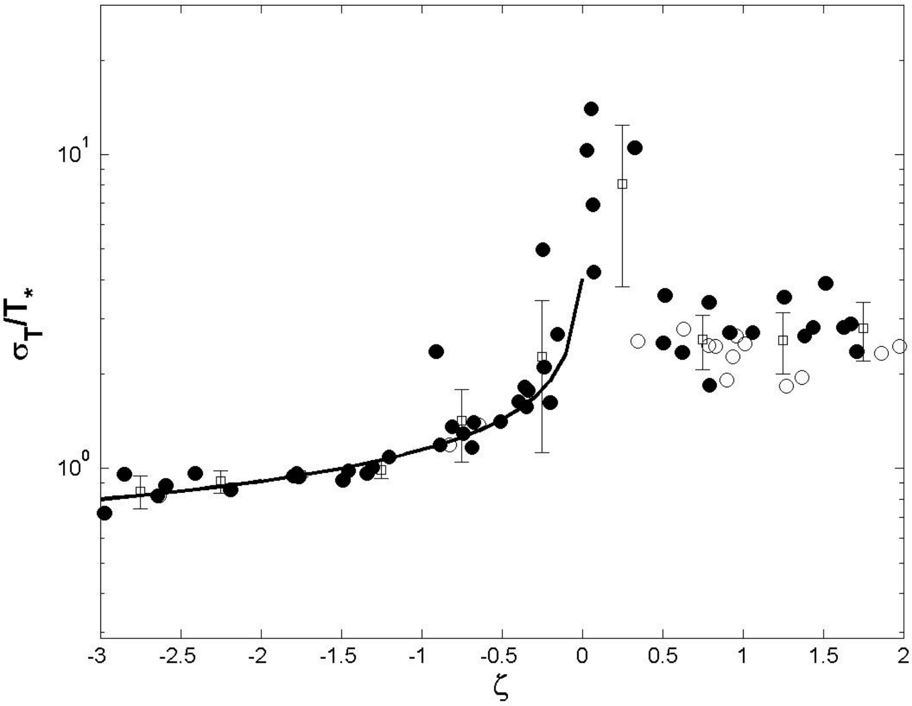

Figure 3 - Normalized standard deviation of the temperature as a function of the stability parameter and the respective standard deviation bars. The black bold line represents $\phi_T(\zeta)$ (Eq. 6). The solid and open circles represent the stationary and non-stationary data, respectively.

Since $\phi_T(\zeta)$ had been determined under unstable condition (Eq. 6), the sensible heat flux is estimated by two independent methods, H_{eddy} and H_{var}, as presented in the Fig. (4). The slope of the linear regression fit, forced through the origin, is 1.02 and coefficient of determination of 0.96. This result is in agreement with the ones found by

Albertson *et al.* (1995) and Katul *et al.* (1995), obtained over uniform and non-uniform terrain.

Hence, the MOST is able to describe the heat transport relationships on the Pantanal region, at least approximately. Indeed, the variance method, that is based on simple measurements of first and second moments of T', allows accurate estimates of H under unstable conditions, even over heterogeneous surfaces such as Pantanal, without direct w' measurements.

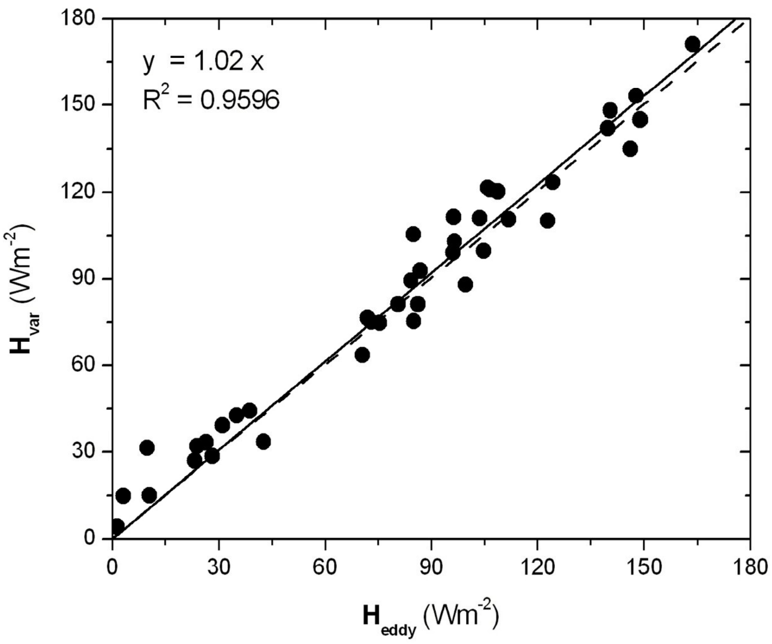

Figure 4 – Comparison between sensible heat flux values estimated by EC $\left(H_{eddy} = \rho c_p \overline{w'T'}\right)$ and variance $\left(H_{var}\right)$ methods (Eq. 5). The lines represent: linear regression fit (solid) and identity function (dashed).

b) Standard deviation of wind velocity

The standard deviation of the wind velocity components provides some useful information about the turbulence intensity. They are also very important to validate the modeling of kinetic energy and turbulent transport in the planetary boundary layer (PBL) (Wyngaard, 1983).

For neutral conditions, the MOST predicts the invariance of the normalized standard deviation of the wind velocity components, $\sigma_{u,v,w}/u_*$ (Panofsky and Dutton, 1984). The Table 1 presents the estimations of $\sigma_{u,v,w}/u_*$ under neutral stability condition on Pantanal compared to other estimations reported in the literature. There is a first order agreement between the available estimates. The observed differences occur probably due to the terrain characteristics, such as land use, non-turbulent motion contributions, instrumental errors, and different heights of measurements (Panofsky and Dutton, 1984; Kader and Yaglom, 1990; Högström, 1990; Al-Jiboori *et al.*, 2001; Högström *et al.*, 2002).

Table 1 – Normalized standard deviations of the wind velocity components under neutral stability condition

σ_w/u_*	σ_u/u_*	σ_v/u_*	References
1.33 ± 0.02	2.21 ± 0.03	1.76 ± 0.03	Pantanal Region
1.20	2.40	2.20	Moraes *et al.* (2005)
1.37	2.32 ± 0.39	2.29 ± 0.22	Krishnan and Kunhikrishnan (2002)
1.10	2.30	2.00	Pahlow *et al.* (2001)
1.20	2.55	-	Andreas *et al.* (1998)
-	2.78±0.25	2.44±0.40	Högström (1990)
1.25	2.70	2.50	Kader and Yaglom (1990)
1.25±0.03	2.39±0.03	1.92±0.05	Panofsky and Dutton (1984)
1.30	-	-	Merry and Panofsky (1976)
1.25	2.30	1.70	Monin and Yaglom (1971)

The MOST predicts that the normalized standard deviation of the wind velocity components are functions of ζ (Kader and Yaglom, 1990; Andreas *et al.*, 1998).

The Fig. 5 shows σ_w/u_* as a function of ζ for the Pantanal, and the resulting fitting curves:

$$\phi_w(\zeta) = (1.58 - 3.86\zeta)^{1/3} \quad \text{for} \quad \zeta < 0 \tag{7a}$$

$$\phi_w(\zeta) = (1.16 + 0.12\zeta) \quad \text{for} \quad \zeta > 0 \tag{7b}$$

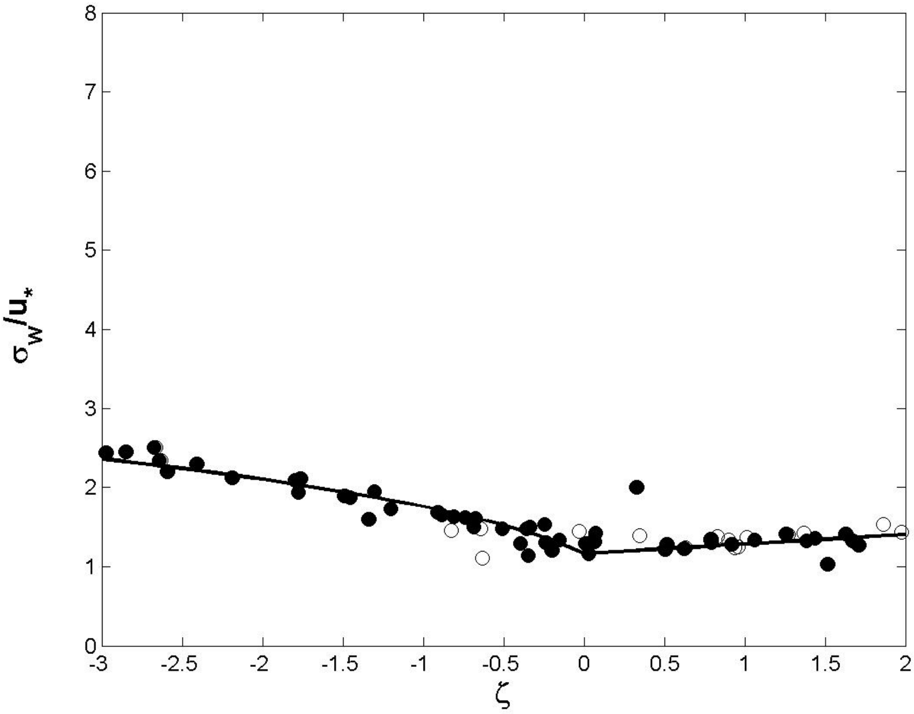

Figure 5 - Normalized standard deviation of the vertical wind velocity as a function of the stability parameter. The solid line represents $\phi_w(\zeta)$ (Eqs. 7a and 7b). The solid and open circles represent the stationary and non-stationary data, respectively.

The $\phi_w(\zeta)$ obtained are lightly inferior to the curve proposed by Panofsky *et al.* (1977) and Kaimal and Finnigan (1994), under unstable and stable conditions, respectively. Towards free convection, σ_w/u_* increase obeying the 1/3 power-law as predict from the literature (Wyngaard *et al.*, 1971).

The normalized standard deviation of the horizontal wind velocity σ_U/u_* $\left(\text{where } \sigma_U^2 = 0.5\left[\sigma_u^2+\sigma_v^2\right]\right)$ as a function of ζ is showed in the Fig. 6. The fitting curves obtained for the Pantanal are given by:

$$\phi_U(\zeta) = (5.23-7.94\zeta)^{1/3} \quad \text{for} \quad \zeta<0 \qquad (8a)$$

$$\phi_U(\zeta) = (1.74+0.36\zeta) \quad \text{for} \quad \zeta>0 \qquad (8b)$$

For stable conditions, $\phi_U(\zeta)$ presents good agreement with the curve proposed by Andreas *et al*. (1998), despite the complexity of the atmospheric turbulent regime, global intermittence, non-turbulent motion contributions and low level jet effects (Mahrt *et al.,* 1998; Mahrt, 1999; Poulos *et al.*, 2002; Sun *et al.*, 2004). Under unstable conditions, $\zeta>-2$, the estimates of σ_U/u_* seems to follow the MOS predictions very well (Kader and Yaglom, 1990).

On the other hand, under free convection, some empirical evidences show that the horizontal velocity fluctuations are influenced by large convectively driven eddies, extending up to the top of the PBL. They suggest that both scales, the PBL height z_i and the convective velocity scaling $w_* = \left[(g/T_0)\left(\overline{w'T'}\right)_0 z_i\right]^{1/3}$, are more appropriated scaling parameters than z and u_* for normalizing the horizontal wind velocity fluctuations in the unstable SL (Deardorff, 1972; Panofsky *et al.*, 1977; Kaimal, 1978; Johansson *et al*., 2001).

During the IPE-1 campaign, the PBL vertical structure data were not available, and direct measurements of the PBL height have not been performed. Then, a mixed layer (ML) slab model (Tennekes, 1973; Oliveira *et al*., 2004) has been used to estimate z_i under strong convective conditions. A top-down entrainment rate of 20 % of the Pantanal surface heat flux H_{eddy} is applied. The temporal evolution of H_{eddy} has been assimilated by a Newtonian's nudging (Haltiner and Williams, 1980) as a boundary condition forcing of the ML slab model. The Tennekes' model is based in the integration of the temperature equation along the vertical levels of ML, considering the application of integral differencing rule.

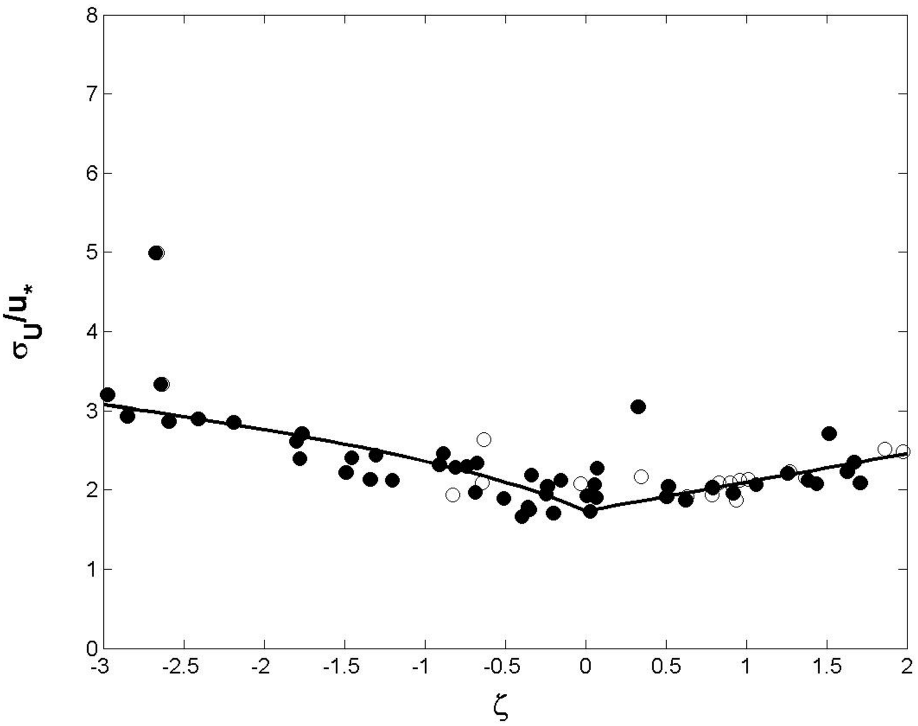

Figure 6 - Normalized standard deviation of the horizontal wind velocity as a function of the stability parameter. The solid lines represent $\phi_U(\zeta)$ (Eqs. 8a and 8b). The solid and open circles represent the stationary and non-stationary data, respectively.

In the Fig. 7 σ_U/w_* has been plotted against z_i/L under free convection, where the solid line represents the fitting curve given by:

$$\frac{\sigma_U}{w_*}\left(\frac{z_i}{L}\right)=\left(0.31-\frac{3.00}{z_i/L}\right)^{1/3} \quad \text{for} \quad z_i/L<0 \ \text{ and } \ \zeta<\text{-}2 \tag{9}$$

which is in agreement with the proposed formulation by Johansson *et al.* (2001).

In order to verify what it is the better adjustment between Eq. (8a) and (9), a RMSE analysis was performed. The RMSE of $\sigma_U/u_* \times \zeta$ and $\sigma_U/w_* \times z_i/L$ were calculated (Table 2) considering fitting curves defined by least square methods. The results confirm the statement z_i and not z is the main characteristic length scale under free convection.

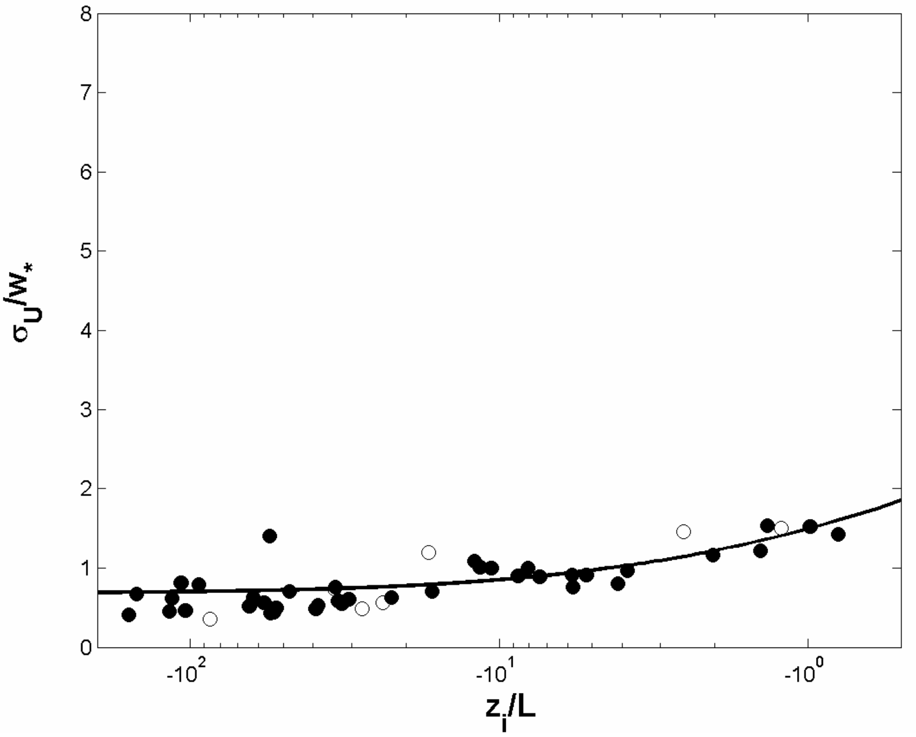

Fig. 7 - Normalized standard deviation of the horizontal wind velocity as a function of the stability parameter z_i/L. The solid line represents σ_U/w_* (Eq. 9). The solid and open circles represent the stationary and non-stationary data, respectively.

Table 2 – RMSE estimated for normalized standard deviation of the wind velocity components under free convection condition

$-30 \leq \zeta \leq -2$	σ_U/u_*	σ_U/w_*
RMSE	1.01	0.25

Kader and Yaglom (1990) had discussed the validity of MOST in function of the measurements heights at relatively smaller. They affirm z_i is the correct length scale when the measurements are made at heights greater than the thickness of the SL.

Despite of the relative success of the universal functions defined by MOST in representing the standard deviation of the wind velocity components under stable condition, Mahrt et *al.* (1998) have reasoned that the relationships can be strongly influenced by self-correlation due to the occurrence of u_* on both sides of the Eqs. (7b and 8b).

According to Klipp and Mahrt (2004) (see their Fig. 2, page 2092), our original set of variables u_*, $\overline{w'T'}$, $\overline{w'q'}, \sigma_{U,w}$ was redistributed in a random and independent way for every variable. This generated a new set of variables with dimension 10 times larger than the original set that presents the same average and variance.

The linear-correlation coefficient estimated for the original set (R_{data}) and the randomized set (R_{rand}) point out that the variance explained by self-correlation is smaller. In the other hand, the same analysis procedure (Table 3) under stable condition, $0.1 < \zeta \leq 2$, supports the idea that self-correlation is significant and the results shown in the Figs. (5 and 6) should be interpreted cautiously. Under neutral conditions, both correlations are small (not showed) and the standard deviation does not depend on ζ, in according to MOST.

The correlation coefficient between two variables is determined by the ratio of their covariance and the product of their respective standard deviations. In the SL the correlation coefficients for the heat $\left(r_{wT} = \overline{w'T'}/\sigma_w\sigma_T\right)$ and momentum flux $\left(r_{uw} = \overline{u'w'}/\sigma_u\sigma_w\right)$ are following the MOST (Kaimal *et al.*, 1972; Kaimal and Finnigan, 1994). The estimations for the Pantanal are showed in the Figs. 8a and 8b, respectively, where the solid line represents the following fitting curve:

$$r_{wT}(\zeta) = 0.81\left[\frac{1}{1+e^{5(\zeta+0.10)}}\right]\text{-}0.30 \qquad \text{for} \quad -3 \le \zeta \le 2 \qquad (10a)$$

$$r_{uw}(\zeta) = 0.18\left[\frac{1}{1+e^{5(\zeta+1.25)}}\right]\text{-}0.32 \qquad \text{for} \quad -3 \le \zeta \le 2 \qquad (10b)$$

Table 3 – Self-correlation analysis

Stability conditions	σ_w/u_*		σ_U/u_*	
	R_{data}	R_{rand}	R_{data}	R_{rand}
$-3 \le \zeta < -0.1$	-0.93	-0.13	-0.78	-0.15
$0.1 < \zeta \le 2$	-0.08	0.44	0.29	0.50

Under unstable conditions the correlation coefficients are $r_{wT} = 0.45 \pm 0.03$ (for $-2<\zeta<0$) and $r_{uw} = -0.31 \pm 0.02$ (for $-1<\zeta<1$) in agreement with the values proposed by Kaimal and Finnigan (1984) for Kansas experiment, $r_{wT} \simeq 0.5$ (for $-2<\zeta<0$) and $r_{uw} \simeq -0.35$ (for $-1<\zeta<1$), respectively.

In according to Högström (1990), $|r_{uw}| < 0.30$ indicates the presence of inactive turbulence associate to the transport of turbulent energy from the layer above by the pressure transport term. Similar results have been found by von Randow *et al.* (2006) in the SL over the Amazonian rain forest. In the Pantanal the correlation coefficients found is near to the expected, and the low frequency contributions seems to be smaller, at least in the range $-3<\zeta<2$ and for 60min averaging time scale.

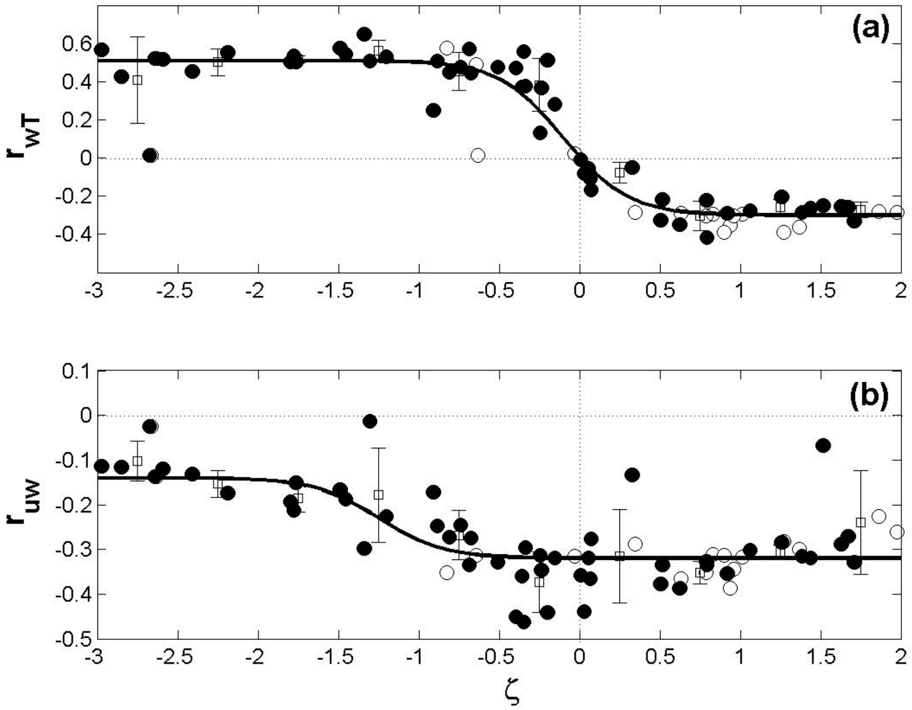

Fig. 8 – Correlation coefficients with the standard deviation bars for: a) heat flux r_{wT} ; b) momentum flux r_{uw} . The solid lines represent the fitting curves for Pantanal (Eqs. 10a and 10b). The solid and open circles represent the stationary and non-stationary data, respectively.

5. Conclusions

The SEB components, the standard deviations of the wind velocity, the standard deviations of the temperature, and the correlation coefficients have been computed above the complex terrain found in Pantanal region in Brazil.

The analysis considers the micrometeorological measurements recorded during the IPE-1 over a vegetated terrain partially covered by a SWL with 7 to 15 cm-depth. The SWL contains a lot of embedded vegetation. The presence of vegetation implies a specific radiation transfer through the depth of the water body and a particular energy budget.

The surface fluxes H, R_n and G_{out} were measured directly, LE and ΔS were estimated by the Bowen ratio method and as a residual term, respectively. The diurnal evolution of SEB components should be understood as a consequence of the great surface heating of SWL and the large LE $(\beta \approx 0.36 \pm 0.01)$.

The determination of d follows the methodology proposed by De Bruin and Verhoef (1997) based in the σ_w under free convection, resulting the value 4.96 ± 0.56.

The MOST predicts the behavior of the normalized standard deviations, under unstable condition, above the Pantanal surface. Both $\sigma_{U,w}/u_*$ and σ_T/T_* are comparable to those found in the literature. The comparison between H values estimated by EC and variance method indicates the general applicability of the MOST for describing the sensible heat flux.

Under neutral condition all normalized standard deviations shows a greater scattering, likely associated with the surface heterogeneities, non-turbulent motions, and instrumental errors. For stable condition, the estimates can be strongly influenced by self-correlation. In the limit of the free convection regime, the proper characteristic scales to normalize σ_U are z_i and w_*. The correlation coefficients are in agreement with the values proposed in the literature. Particularly, the presence of low frequency contributions was not identified.

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