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Some aspects of the structure of the stratified atmospheric boundary layer of N-E Brazil(*)(**)

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Summary. — The preliminary results of an analysis based on the experiment "Experimento de Microfisica de Nuvens—EmfiN" (Experiment of Microphysics of Clouds), conducted by Universidade Estadual de Ceara—UECE at Fortaleza (3.77 S and 38.60 W), a semi-arid tropical region of N-E Brazil, are presented. The kinematic stresses are computed by the layer integration of the Planetary Boundary Layer (PBL) momentum equation for horizontally homogeneous turbulence above the viscous sublayer condition and considering that the inertial acceleration terms could be neglected compared to the Coriolis force and pressure gradient force. The computed stress profiles are in good agreement with the results reported in the literature.
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1. – Introduction

Land-atmosphere coupling is widely recognized as a crucial component of regional-, continental- and global-scale numerical models. Predictions from these large-scale models are sensitive to small-scale surface layer processes like heat and momentum fluxes at the air-soil-vegetation interface as well as boundary layer treatments [1]. Almost 60% of the mean annual energy supply to the atmosphere passes through the PBL from the ground to the free atmosphere in the forms of the sensible and latent heat [2]. Atmospheric drag by boundary-layer friction is the mechanism through which the atmosphere receives much of its angular momentum from the Earth's rotation in the region of easterly winds

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near the equator, while much of the atmospheric kinetic energy is destroyed in the PBL at higher latitudes. Also, all the moisture supplied to the atmosphere passes through the PBL. General circulation models with only a few layers inside the PBL are unable to resolve the complex spatial and temporal structure of PBL turbulence. There are a number of different methods to compute the exchange processes inside the PBL. The most physically complete is a second-order closure model [3]. These methods, however, require a rather fine spatial grid on which the coupled set of differential equations are solved numerically. Implementations of such PBL schemes in GCM require a sacrifice in either overall numerical efficiency of the GCM or accuracy of the simulation due to low numerical resolution. Simpler methods, which contain less physical feedback mechanisms, can be devised. Although they require more idealizing assumptions in their design, they are able to reproduce the most important PBL features realistically [4] and have the advantage of being numerically more efficient. The realism of the idealized model can be improved by calibrating it against observational data.

During the past decade land-surface-models (LSM) have improved continuously, especially with the help of field experiments, like First ISLSCP (International Satellite Land Surface Climatology Project—FIFE [5], the Boreal Ecosystem-Atmospheric Study—BOREAS [6], the Hydrologic and Pilot Experiment in the Sahel—HAPEX-Sahel [7], the Northern Hemisphere Climate Processes—NOPEX [8], Observations at Several interacting Scales—OASIS [9], etc. Because of the increasing awareness that tropical rain forest and the continental rain forest of the Amazon basin in particular may have an important role in global climatology, there have been a number of international projects on Amazon basin in Brazil as Anglo-Brazilian collaborative study of the micrometeorology and plant physiology of Amazon rain forest—Amazonian, Regional Micrometeorological Experiment—ARME [10-12], ABRACOS—Anglo Brazilian Amazonian Climate Observation Study [13] and LBA—Large Scale Biosphere-Atmosphere Experiment in Amazon [14]. However, evaluation is still needed for semi-arid regions [15] specially, for the North East (N-E) region of Brazil. But in this region, most of the works are confined to the energy balance using Bowen ratio method, and mostly published in congress proceedings (in Portuguese) some of which may be found in [16-18]. Recently Patel *et al.* [19] have estimated the kinematic fluxes of sensible heat and water vapor of the surface boundary layer of the semi-arid tropical region of N-E Brazil, by the thermodynamic energy and water vapor conservation equations; and by the Monin-Obukhov similarity theory (MOST). The results of the two methods used by them are in good agreement. Further they have shown that in the absence of sophisticated fast-response turbulence instrumentation and wind data the conservations equations methods are better options for estimation of heat and water vapor fluxes and also useful to study the turbulent fluxes in inhomogeneous condition in time like early morning and late evening boundary layer transitions. But these results obtained by Patel *et al.* [19] are for the surface boundary layer, the so-called constant flux layer rather than the whole atmospheric boundary layer (ABL). So it is important to study some characteristics of the vertical structure of the stratified Atmospheric Boundary Layer of semi-arid tropical region of N-E Brazil to help better understand the parameterization of turbulent fluxes for applications, among others, in regional multilayer models.

2. – Experimental data

In this study the data of the balloon sounding collected in Fortaleza (3.77 S and 38.60 W) a semi-arid tropical region of N-E Brazil, during the period 02-04-2002 to

11-04-2002 as a part of the experiment EmfiN—experimento de Microfisica de Nuvens (experiment of microphysics of clouds) conducted by Universidade Estadual da Ceara—UECE were used. The experimental site is extensive with small grasses and can be considered as quasi-homogeneous terrain. The Marwin-Vaisala RS-90 balloons were used in this experiment. In total 28 balloons were launched. But it was observed during the initial data analysis, that the wind data from 08 balloons, two each day of 04-04-2002, 05-04-2002, 06-04-2002 and 09-04-2002 were lost. The two days (06-04-2002 and 08-04-2002) balloon data of this experiment were also used by Patel *et al.* [19] to study the mean kinematic fluxes of sensible heat and water vapor of surface boundary layer. In this preliminary study only three days of the following data of wind velocity and potential temperature are analyzed (see table I) to study the vertical structure of Reynolds stresses in the atmospheric boundary layer.

TABLE I. – *Details of soundings used.*

Day	Local time	Code
03-04-2002	11:42	03041142
08-04-2002	0725	08040725
08-04-2002	11:03	08041103
08-04-2002	12:49	08041249
09-04-2002	0815	09040815
09-04-2002	14:37	09041437

3. – Methodology and discussion

a) *Stress profile*

The planetary boundary layer momentum conservation equation for horizontally homogeneous turbulence above the viscous sublayer may be written in the form

$$\frac{\partial \bar{U}}{\partial t} - f(\bar{V} - \bar{V}_{\mathrm{g}}) = -\frac{\partial \overline{u'w'}}{\partial z}, \tag{1}$$

$$\frac{\partial \bar{V}}{\partial t} + f(\bar{U} - \bar{U}_{\mathrm{g}}) = -\frac{\partial \overline{v'w'}}{\partial z}, \tag{2}$$

where $\bar{U}_{\mathrm{g}}$ and $\bar{V}_{\mathrm{g}}$ are the components of geostrophic wind, f is the Coriolis parameter, t is time, $\bar{U}, \bar{V}$ are the mean and u', v' are the fluctuating part of the wind component. The kinematic longitudinal and lateral stresses are given by

$$\tau_x = -\overline{u'w'} \qquad \text{and} \qquad \tau_y = -\overline{v'w'}\,. \tag{3}$$

Considering that the inertial acceleration terms could be neglected compared to the Coriolis force and pressure gradient force, eqs. (1) and (2) may be written as

$$\frac{\partial \overline{u'w'}}{\partial z} = f(\overline{V} - \overline{V_{\mathrm{g}}}), \tag{4}$$

$$\frac{\partial \overline{v'w'}}{\partial z} = -f(\overline{U} - \overline{U_{\mathrm{g}}}). \tag{5}$$

From eqs. (4) and (5), the values of turbulent transport terms ($\overline{u'w'}$ and $\overline{v'w'}$) can be obtained by integrating with respect to height from 0 (surface) to h (the height of the PBL). The PBL height (h) for this study is estimated as a height at which the wind velocity is maximum, for corresponding sounding. This is based on the assumption, implied by the gradient transport hypothesis, that $\overline{u'w'}$ and $\overline{v'w'}$ must vanish at the levels where $\partial\bar{U}/\partial z$ and $\partial\bar{V}/\partial z$, respectively, become zero [20]. The wind at the 850 hPa levels from the corresponding sounding may be considered as an approximation to the geostrophic wind [21]. But, in this study the values of $\bar{U}_{\mathrm{g}}$ and $\bar{V}_{\mathrm{g}}$ are obtained from the conditions given by [20, 22]

$$\bar{U} \to \bar{U}_{\mathrm{g}}\,, \qquad \text{and} \qquad \bar{V} \to \bar{V}_{\mathrm{g}} \qquad \text{for} \quad z \to h \tag{6}$$

for corresponding sounding. The values of $\bar{U}_{\mathrm{g}}$ and $\bar{V}_{\mathrm{g}}$ obtained by these two methods are found to be approximately the same.

The Reynolds stress ($\overline{u'w'}$) profiles are obtained by integrating eqs. (4) and (5) with respect to height, using the corresponding values for each sounding. Then the turbulent stress profiles may be plotted against height for each sounding. But following [23, 24], in this study the normalized longitudinal stress ($\overline{u'w'}/u_*^2$) profiles with normalized height (fz/u_*) are presented in fig. 1 for each sounding, where u_* is the velocity scale or friction velocity. The values of u_* are used only for the sake of normalization, which may be obtained for each sounding using the well-known Monin-Obukhov similarity theory (MOST). However, for completeness a brief description of the estimation of the velocity scale is provided below.

b) *Estimation of the velocity scale*

The velocity scale is obtained from the wind profile given by

$$\bar{U} = (u_*/\kappa)[\ln(z/z_0) - \Psi_M(z/L_M)]\,. \tag{7}$$

Equation (7) may also be written in the form

$$\ln z - \Psi_M(z/L_M) = (\kappa/u_*)\bar{U} + \ln z_0\,, \tag{8}$$

where $\kappa = 0.4$ is the von-Kárman constant, z_0 is the surface roughness, Ψ_M is the stability function for momentum, which may be obtained from the most commonly used forms known as Bussinger-Dyer formulae [25],

$$\Psi_M(z/L_M) = -5z/L_M\,, \qquad \text{for} \quad z/L_M \geqslant 0\,, \tag{9}$$

$$\Psi_M(z/L_M) = \ln\left[\left(\frac{1+x^2}{2}\right)\left(\frac{1+x}{2}\right)^2\right] - 2\tan^{-1}x + \frac{\pi}{2}\,, \qquad \text{for} \quad \frac{z}{L_M} < 0\,, \tag{10}$$

where $x = (1 - 15z/L_M)^{1/4}$ and L_M is the Monin-Obukhov length scale given by

$$L_M = -\frac{u_*^3 T_0}{\kappa g \overline{wT'}}\,, \tag{11}$$

where T_0 is the mean absolute temperature in Kelvin, g is the acceleration due to gravity and $\overline{w'T'}$ is the heat flux. The values of (z/L_M) may be obtained from the equations

$$(12)\quad z/L_M = \mathrm{Ri}\,, \quad \text{for} \quad \mathrm{Ri} < 0 \qquad \text{and} \qquad z/L_M = \mathrm{Ri}/(1-5\mathrm{Ri}) \quad \text{for} \quad 0 \leqslant \mathrm{Ri} < 0.2\,,$$

where Ri is the Richardson number defined as

$$(13)\qquad \mathrm{Ri} = \frac{g}{T_0}\frac{\partial\bar{\Theta}}{\partial z}\left(\frac{\partial\bar{U}}{\partial z}\right)^{-2},$$

where $\overline{\Theta}$ is the mean potential temperature.

The Richardson number (Ri) is obtained from the corresponding velocity and potential temperature profiles for each sounding. Then from eq. (12) the value of z/L_M for the appropriate stability condition is obtained and substituting the value of z/L_M in eq. (9) or (10) (depending upon the stability), the stability function $\Psi_M(z/L_M)$ is obtained for each sounding. Finally, the velocity scale (u_*) is obtained, by applying the least-square regression method for $\ln z - \Psi_M$ *vs.* $\bar{U}(z)$ at various heights of the observations of velocity from the corresponding balloons, as the slop of eq. (8).

The normalized stress distributions plotted against the normalized height are shown in fig. 1, for the corresponding balloons for the periods given in table I. The normalized stress vertical variation patterns are in good agreement with the results reported in the literature [23, 24, 26-39] obtained by different approaches —micrometeorological experimental observations [24, 26-29], higher-order closure models [30-33], Large Eddy Simulations (LES) [34-37] and numerical simulations [38, 39]. However the actual shapes of the vertical stress distributions vary slightly depending upon the scales used in plotting the figures; like $\overline{u'w'}$ *vs.* z/h (h is the height of the ABL) [26, 28, 29], $\overline{u'w'}/u_*^2$ *vs.* z/h [32], $\overline{u'w'}$ *vs.* z [30, 31, 33] and $\overline{u'w'}/u_*^2$ *vs.* fz/u_* [23, 24, 37], etc. In this study the last scales are used, so that at any height within the ABL the calculated stress can be compared with the corresponding surface stress (u_*^2) obtained by the MOST. All these results show the anomalous variations of stress with height. In the barotropic, nonentraining, convective boundary layer the stress $\overline{u'w'}$ is expected to decrease monotonically with height, approaching zero at h, the height of the atmospheric boundary layer. These types of anomalous variations are due to the effect of baroclinicity [40], entrainment of momentum in the upper portion of ABL [41], nonstationarity and advective forcing [27]. So, the nature of height-integrated ageostrophic flow within the ABL is influenced not only by surface friction but also by additional effects including baroclinicity, nonstationarity, advective forcing and boundary layer-top entrainment. Many experimental studies on the atmospheric boundary layer have been reported in the literature. But these types of experiments conducted in the semi-arid tropics are rare compared with those conducted in extratropical and mid-latitude regions. In the tropics, significant diurnal oscillations in wind speed, static stability, turbulent exchange, and convective activity are observed within the atmospheric boundary layer [42, 43]. So, in the absence of such field experimental results in the semi-arid tropical region of N-E Brazil, the results of this study could not be compared.

The Monin-Obukhov similarity theory (MOST) is one of the most important tools in describing the atmospheric boundary layer (ABL) and the Monin-Obukhov similarity empirical functions are now used in many practical applications of micrometeorology [44, 45]. But it describes better the atmospheric surface layer (ASL) the so-called constant flux layer rather than the whole ABL. The height-dependences of the vertical turbulent fluxes

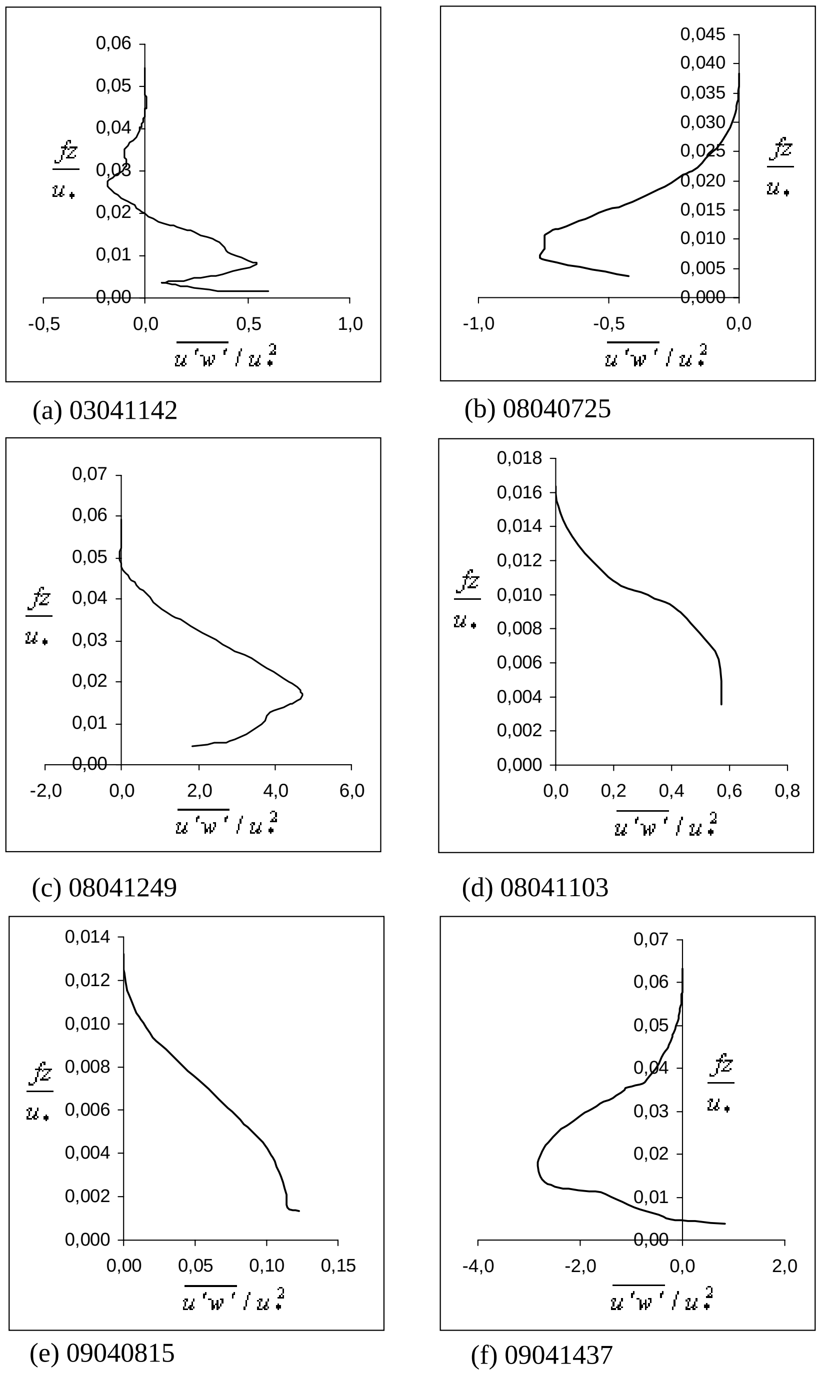

Fig. 1. – Stress profile for different soundings.

are generally assumed to be negligible within the surface boundary layer [46] under stable as well as unstable conditions. Haugen *et al.* [47] concluded that the vertical variations of fluxes in the surface layer are within ±20%. Yague and Cano [48] found that under stable conditions the height independence of flux assumption is better for heat than for momentum. Because of the problems encountered in parameterization of the weak and very stable boundary layer in numerical models, including large eddy simulation, mesoscale models and large-scale models, there is growing interest to access among others the height dependence of turbulent fluxes and their departure from the similarity theory in atmospheric surface layer especially under weakly stable and very stable conditions [48-50], etc. The eventual improvement of parameterizations in this regard is presumed to have a significant impact on nocturnal temperature prediction, representation of vertical structure of stratification and consequent daytime convective boundary layer (CBL) growth, and constituent dispersion in stably stratified conditions [51]. Still, the MOST is applied in modern numerical weather prediction models [52]. As discussed earlier the velocity scale (u_*) obtained from the similarity theory is used in this study, only for the sake of normalization. Thus the results of this study show the structure of the kinematic momentum flux profiles in the whole ABL rather than the constant flux layer, and so give a better picture of the vertical stress distribution in the whole ABL for the semi-arid tropical region of N-E Brazil. So in the absence of sophisticated fast-response turbulence instrumentation and micrometeorological tower measurements the results of this study are useful to help better understanding the parameterization of the turbulent momentum flux for applications, among others, in regional multilayer models. This is only a preliminary analysis of the data; the further quantitative details of the results will be presented in a future paper.

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