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# Turbulent fluxes in atmospheric boundary layer of a semi-arid region of N-E Brazil(*)(**)

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**Summary.** — The preliminary results of the experiment “Experimento de Microfisica de Nuvens-EmfiN” (Experiment of microphysics of clouds) conducted by Universidade Estadual de Ceara-UECE at Fortaleza, a semi-arid region of N-E Brazil, are presented. The mean kinematic fluxes of sensible heat and water vapor of the surface boundary layer are estimated by the thermodynamic energy and water vapor conservation equations; and by the Monin-Obukhov similarity theory. The results of the two methods are in good agreement. It is shown that in the absence of sophisticated fast-response turbulence instrumentation and wind data the conservations equations methods are better option for estimation of heat and water vapor fluxes. Further they are useful to study the turbulent fluxes in inhomogeneous condition in time like early morning and late evening boundary layer transitions.

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## 1. – Introduction

The importance of land surface processes on atmospheric boundary layer development and larger-scale weather has been widely studied for over 30 years. Reviews by Betts *et al.* [1] and Pielke *et al.* [2] detail how exchanges of energy, moisture and momentum between the atmospheric boundary layer and the land surface are strongly influenced by vegetation and soil moisture. Changes in the land surface and the atmospheric boundary layer impact larger-scale weather through entrainment with the troposphere and convective cloud formation [3]. During the past decade land-surface models (LSM) have

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Table I. – *Details of soundings used.*

| Day | Local time | Code |
|---|---|---|
| 06-04-2002 | 10:33 | 06041033 |
| 06-04-2002 | 11:50 | 06041150 |
| 08-04-2002 | 11:03 | 08041103 |
| 08-04-2002 | 12:49 | 08041249 |

improved continuously, especially with the help of field experiments like First ISLSCP (International Satellite Land Surface Climatology Project—FIFE [4], the Boreal Ecosystem-Atmospheric Study—BOREAS [5], the Hydrologic and Atmospheric Pilot Experiment in the Sahel—HAPEX-Sahel [6], the Northern Hemisphere Climate Processes—NOPEX [7], Observations at Several Interacting Scales—OASIS [8], 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 Region Micrometeorological Experiment—ARME [9-11], Anglo-Brazilian Amazonian Climate Observation Study—ABRACOS [12] and Large Scale Biosphere-Atmosphere Experiment in Amazon—LBA [13]. However, evaluation is still needed for semi-arid regions [14], specially the North region of Brazil. But in this region most of the works are confined to the energy balance using Bowen ratio method [15-18]. So, it is important to study some characteristics of the Atmospheric Boundary Layer (ABL) of a semi-arid region of N-E Brazil to better understand the parameterization of turbulent fluxes for applications among others, in regional models.

## 2. – Experimental site and data

In this study the data of the balloon sounding collected at Fortaleza (3.77S and 38.60W) a semi-arid 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. In total 28 balloons were launched. But in this preliminary study only two days of the following data are analyzed (see table I).

## 3. – Methodology and discussion

It was observed that out of 28 balloons 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. So to estimate the surface layer fluxes of heat and water vapor for these days, the thermodynamics energy and humidity conservation equations methods are applied and compared by the most commonly used Monin-Obukhov similarity theory (MOST) [19, 20].

### a) *Thermodynamic energy and water vapor conservations equations methods*

The thermodynamic energy equation method, for estimation of sensible heat flux at the surface and its vertical distribution (profile) in the Planetary Boundary Layer (PBL) in the absence of temperature advection, reduces to

$$\frac{\partial \bar{T}}{\partial t} = \frac{1}{\rho c_P} \frac{\partial R_{\mathrm{N}}}{\partial z} - \frac{\partial \overline{w'\theta'}}{\partial z}, \tag{1}$$

where $\rho$ is the density of air, $c_P$ the specific heat of air, $R_{\mathrm{N}}$ is the net radiation, $\bar{T}$ is the mean temperature, $\theta'$ is the temperature fluctuation, $w'$ is the fluctuation of the vertical velocity, $t$ is time and $z$ is height.

Here the time-tendency (warming or cooling rate) is retained, because it is often found to be significant even when the flow field may be considered quasi-stationary. It is a manifestation of diurnal heating and cooling cycle, which is responsible for important stability and buoyancy effects in the PBL. From eq. (1) one may see that the rate of warming or cooling essentially balances the convergence or divergence of radiative and sensible heat fluxes. The radiative flux divergence is usually ignored in the daytime unstable or convective boundary layer, especially in the absence of fog and clouds within the PBL. It becomes more significant in the stably stratified nocturnal boundary layer. For simplification if radiative flux divergence may be ignored the integration of eq. (1) with height yields

$$(\overline{w'\theta'})_0 = \int_0^h \frac{\partial \bar{T}}{\partial t} \mathrm{d}z, \tag{2}$$

where $(\overline{w'\theta'})_0$ is the kinematic sensible heat flux at the surface, $h$ is the height of the PBL. In obtaining eq. (2) it is assumed that at the top of the PBL the sensible heat flux vanishes.

Similarly, from the conservation equation for water vapor, one may have the kinematic water vapor flux as

$$(\overline{w'q'})_0 = \int_0^h \frac{\partial \bar{q}}{\partial t} \mathrm{d}z, \tag{3}$$

where $\bar{q}$ is the mean specific humidity and $q'$ is the fluctuation of the specific humidity. In obtaining eq. (3) it is also assumed that at the top of the PBL $(\overline{w'q'})_h = 0$.

b) *Estimation of fluxes by MOST (profile method)*

The most commonly used flux profile relationships are based on MOST. MOST predicts that the non-dimensional gradient of velocity temperature and humidity are universal functions of atmospheric stability

$$\phi_x \left( \frac{z}{L_{\mathrm{M}}} \right) = \frac{\kappa z}{x_*} \frac{\partial X}{\partial z}, \tag{4}$$

where $\partial X / \partial z$ and $x_*$ are the gradient and scaling parameter for velocity, temperature or humidity, $z$ is the height above the surface, $\kappa = 0.4$ is von Karman's constant and $L_{\mathrm{M}}$ is the Monin-Obukhov (MO) length given by

$$L_{\mathrm{M}} = -\frac{\rho c_P u_*^3 T_0}{\kappa g H}.$$

The corresponding profiles may be written in the form

$$\bar{U} = (u_*/\kappa)\Big[\ln(z/z_0) - \Psi_\mathrm{M}(z/L_\mathrm{M})\Big]\,, \tag{5}$$

$$(\bar{\Theta} - \bar{\Theta}_0) = (T_*/\kappa)\Big[\ln(/z_0) - \Psi_\mathrm{H}(z/L_\mathrm{M})\Big]\,; \tag{6}$$

$$(\bar{q} - \bar{q}_0) = (q_*/\kappa)\Big[\ln(z/z_0) - \Psi_\mathrm{E}(z/L_\mathrm{M})\Big]\,.$$

From eqs. (5) and (6) one may have

$$\ln z - \Psi_\mathrm{M} = (\kappa/u_*)\bar{U} + \ln z_0\,, \tag{7}$$

$$\ln z - \Psi_\mathrm{H} = (\kappa/T_*)\bar{\Theta} - (\kappa/T_*)\bar{\Theta}_0 + \ln z_0\,, \tag{8}$$

$$\ln z - \Psi_\mathrm{E} = (\kappa/q_*)\bar{q} - (\kappa/q_*) + \ln z_0\,,$$

where $u_*$ is the friction velocity or velocity scale, $T_* = -H_0/(\rho c_P u_*)$ the temperature scale, $q_* = E/(\rho u_*)$ the specific humidity scale, $\kappa$ is von Karman's constant, $H$ is the sensible heat flux and $E$ is the water vapor flux, $g$ is the acceleration due to gravity, $\Psi_\mathrm{M}$, $\Psi_\mathrm{H}$ and $\Psi_\mathrm{E}$ are the stability functions. These flux-profile relationships have been investigated during over land experiments since mid-sixties. These experiments have generated a number of similar semi-empirical functions, with the most commonly used forms known as Businger-Dyer formulae [21].

So the kinematic fluxes for heat flux and water vapor may be written in the form

$$\frac{H}{\rho c_P} = -u_* T_* \qquad \text{and} \qquad \frac{E}{\rho} = -u_* q_*\,. \tag{9}$$

Applying the least-square regression method for $\ln z - \Psi_\mathrm{M}$ *vs.* $\bar{U}(z)$, $\ln z - \Psi_\mathrm{H}$ *vs.* $\bar{\Theta}(Z)$; and $\ln z - \Psi_\mathrm{E}$ *vs.* $\bar{q}$ at the various heights of the observations of velocity, potential temperature land specific humidity from the soundings, the values of the velocity, temperature and humidity scales are estimated from the slops of the corresponding equations ((7) and (8)) and consequently the kinematic fluxes of heat and water vapor are obtained from eq. (9).

TABLE II. – *Comparison of the mean kinematic heat fluxes.*

| | | Heat | |
|---|---|---|---|
| Date | Hour | Eq. (9) | Eq. (2) |
| 6/April | 10:33–11:50 | 0.030509 | 0.7232 |
| 8/April | 11:03–12:49 | 1.514075 | 1.7956 |

TABLE III. – *Comparison of the mean kinematic fluxes of water vapor.*

| Water vapor | | | |
|---|---|---|---|
| Date | Hour | Eq. (9) | Eq. (3) |
| 6/April | 10:33–11:50 | 0.91229 | 0.7675 |
| 8/April | 11:03–12:49 | 1.338492 | 1.1137 |

The kinematic fluxes are calculated from the accumulation methods (eqs. (2) and (3)) and from profiles methods (eqs. (9)). The height of the PBL is estimated as a height where the velocity gradient is zero [22] in corresponding sounding.

The calculated values by both methods for the mean kinematic heat fluxes (K m $s^{-1}$) are shown in table II and the kinematic water vapor fluxes (m $s^{-1}$) in table III.

It can be seen from tables II and III that there are good agreements between the results of the mean kinematic fluxes of heat and water vapor estimated by thermodynamic energy and water vapor conservations equations, and the MOST. The differences of the results from two methods are consistent with the generally estimated uncertainties in estimates of surface fluxes using various micrometeorological methods [22]. In recent years, most of the planetary boundary layer researches are directed towards the understanding of turbulent fluxes in inhomogeneous conditions, either in time or space. The morning and evening boundary layer transitions are good examples of the inhomogeneous condition in time because of the transition between the stable nocturnal boundary layer and the convective daytime boundary layer over land. The morning transition (MT) is also important to air quality studies because of the differing concentration of pollutants that occur in the nocturnal boundary layer (BL) and the overlaying residual layer. Knowing the timing of the MT is especially important during the summertime because it often

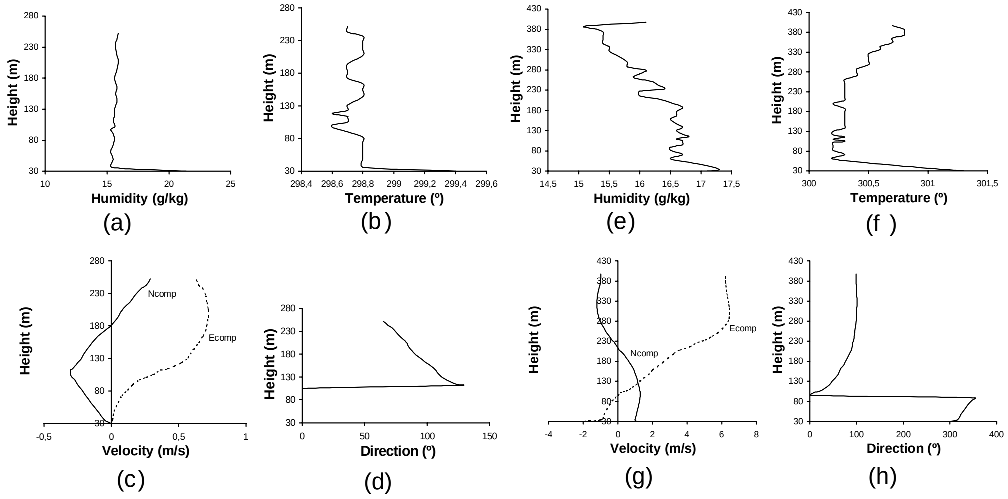
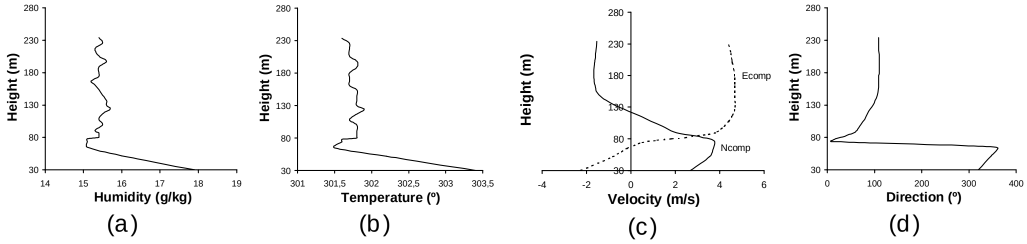


Fig. 1. – Left (a, b, c, d): Sounding on 06 April 2002, 11:50; right: (e, f, g, h): sounding on 08 April 2002, 12:49.



(a) (b) (c) (d)

Fig. 2. – Sounding: 08 April 2002, 11:03.

occurs during the period of increased anthropogenic and biogenic emissions. Yet, the MT is one of the more difficult features to simulate properly in numerical models because of insufficient vertical resolution near the ground and the BL parameterization physics. The behavior of the atmospheric boundary layer (ABL) during the period between the fully developed convection of the afternoon and the stable conditions of the nocturnal boundary layer (NBL) is poorly understood and is of interest in several areas, including chemical and pollutant modeling. Normally the MOST assumes the time-independent condition, so in this case the thermodynamic energy balance and water vapor conservation equations may be more useful than the MOST. This is just a preliminary result of the experiment; further more quantitative results will be presented in a future paper.

The temporal evolution of the soundings for specific humidity, potential temperature, wind speed and direction are shown in figs. 1 and 2.

So, in the absence of sophisticated fast-response turbulence instrumentation and micrometeorological tower measurements, the thermodynamic energy and humidity conservation equations are quite useful in that these are based on the fundamental conservation equations and measurements of mean temperature and humidity profiles without any restrictive assumptions. Also, in the absence of the wind data this method is useful to estimate the surface layer heat and water vapor fluxes. Further, this method is useful to study the understanding of the turbulent fluxes in inhomogeneous condition in time, like early morning and late afternoon boundary layer transitions, which are important also in air quality study.

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