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ANALYSIS OF DIABATIC WIND AND TEMPERATURE PROFILES OVER THE AMAZONIAN FOREST

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ABSTRACT The micrometeorological research program for the Amazonian Forest has provided extensive data on wind and temperature profile structures under lapse to extreme inversion conditions. Significant variations in the determinations of surface roughness (z_0) and zero-plane displacement (d) from quasi-neutral wind profiles are noted. Differences in the shear stress (τ) are largely dependent on the selected z_0 and d. The Deacon numbers for wind (β_u) and potential temperature (β_θ) were computed, to investigate in detail the curvatures of these profiles. A relation between β's and Richardson gradient number (Ri) is obtained. The empirical relationship between the β's and Ri seems to become erratic for strong inversion conditions. The ratio K_H/K_M is greater than unity for all stabilities and slowly decreases for large values of Ri. This study shows that it is possible to compare the results of observed data with theoretical models.

INTRODUCTION

In the past, several theoretical and experimental studies (Monin and Yaglom, 1977; Viswanadham, 1982; McCaughey, 1985 and Sá *et al.*, 1988) were carried out to study the atmospheric turbulence and the radiation and energy balances. Much research has been done on these processes in the atmospheric boundary layer above a horizontal and homogeneous plane with small surface roughness. For various reasons, radiation and turbulent exchanges above forests have been studied less intensively. At the same time, there has been an increasing awareness about the tropical evergreen rain forests of the Amazonian basin, Brazil. These forests may play an important role in the global climates. Measurements of various meteorological parameters for this important vegetation type represent a significant gap in the literature.

This work describes some results from a large project of a major Anglo-Brazilian collaborative study of the micrometeorology of the Amazonian rain forest. In the past five years, seven experiments in the Ducke Reserve Forest (DRF) site (2°57′S; 59°57′W) in the Amazon basin, Amazonas, Brazil were completed. The data sets collected during the second (15 March to 5 May, 1984) and the fifth (1 July to 30 August, 1985) campaigns are used to study the curvatures of wind and temperature profiles. Due to limited space, a brief report about the Deacon numbers (Deacon, 1949) versus the Richardson gradient number is presented. This representation is an attempt to examine the proposed theoretical models for the surface layer of the atmosphere.

THEORETICAL RELATIONSHIPS

When the ground cover is high enough such that significant turbulent flow can occur below the top of a canopy, the Deacon (1949) vertical wind shear in the diabatic conditions can be represented as

$$\frac{du}{dz} = a(z-d)^{-\beta}, \quad \text{for } z \geq D \tag{1}$$

The simplest mathematical form which expresses the vertical curvature is the parameter β and it can be obtained by the logarithmic differentiation of Deacon's (1949) wind profile (derived from Eq. (1)) if β is sufficiently small so as to be neglected (Lettau, 1956). The Deacon numbers of the wind (β_u) and temperature (β_θ) are

$$\beta_u \equiv \frac{\partial\, ln u'}{\partial ln z} = -\,\frac{(z-d)u''}{u'}, \quad \text{and} \tag{2}$$

$$\beta_\theta \equiv \frac{\partial ln \theta'}{\partial ln z} = -\,\frac{(z-d)\theta''}{\theta'} \tag{3}$$

The Richardson gradient number (Ri) is

$$Ri = \frac{g}{\overline{\theta}}\,\frac{\theta'}{(u')^2} \tag{4}$$

Here $a = u_*/kz_0^{1-\beta}$, u_* is friction velocity, u is horizontal wind speed, θ is potential temperature, z is height, k is von Karman's constant (=0.40), D = d + z_0 (where d is the zero-plane displacement and z_0 roughness parameter), θ is the average temperature of the layer and g is gravity. The primes denote differentiations with respect to z or z-d. It follows directly from Eqs. (2-4) that

$$\frac{\partial ln\, Ri}{\partial ln z} \equiv \frac{(z-d)\,(Ri)'}{Ri} = 2\beta_u - \beta_\theta \tag{5}$$

Using turbulent heat and momentum flux relations and Eqs. (2-4), the following expression can be obtained

$$\frac{\partial ln F}{\partial ln\, Ri} = -\,\frac{(\beta_u-\beta_\theta)}{(2\beta_u-\beta_\theta)} = -\,\frac{\delta}{\Delta} \tag{6}$$

where $F = K_H/K_M$ (K_H, K_M are eddy diffusivity coefficients for heat and momentum, respectively).

Several special cases of Eq. (5) are of interest. They are: (i) $2\beta_u - \beta_\theta = 1$ (i.e., the Ri is linear in z); (ii) $2\beta_u = \beta_\theta$ (i.e., the Ri is independent of z); (iii) $\beta_u = \beta_\theta$ (i.e., the Ri is inversely related to u). The third case involves a similarity assumption which is especially important and frequently used in micrometeorology.

EXPERIMENTAL SITE AND MEASUREMENTS

The place selected for the experiment is in the tropical evergreen forests of the Amazonas basin, Brazil. The measurements were made using a 45 m scaffolding tower at a site (2° 57' S; 59° 57' W), situated in the Ducke Reserve Forest (DRF), 26 km from Torquato Tapajos Highway, Manaus, Amazonas. The altitude of the DRF site is 84 m above the mean sea level. The DRF belongs to the Instituto Nacional de Pesquisas da Amazonia (INPA), Manaus, Amazonas, Brazil.

The topography of the basin is gently undulating with valleys several tens of meters deep occurring at about 300 m intervals. About 75% of the basin is covered with natural forest. The topography of the canopy top is modulated by the differential growth of the vegetation. The tower is sited near the top of a broader than average ridge. The eddy correlation and profile measurements described in this paper assume that the fluxes are one-dimensional and an adequate fetch is required for this assumption. The tower has fetches of undisturbed forest extending more than ten kilometers in most directions. A common intuitive rule among micrometeorologists was for a height/fetch ratio range of 1/100 to 1/500 (Bradley, 1968; Fritschen *et al.* 1973). This ratio was necessary if a 90 percent level of shear stress adjustment was acceptable. It is derived on the basis of turbulent boundary layer theory at a rigid wall.

An adequate survey of the climate of the Amazonas basin is a difficult task because the network of stations is very meager in vast regions of the Amazonas basin. Some details are presented in Sa' *et al.* (1988).

The momentum, sensible heat and evaporation fluxes were measured with a "Hydra", a battery-powered eddy correlation flux measuring device developed by the Institute of Hydrology, Wallingford, U.K. The instrument was mounted on a pole above the tower at a height of 48.4 m. Further details about the measurements of Hydra are described in Shuttleworth *et al.* (1982) and Sa' *et al.* (1988). The Hydra system cannot provide reliable measurements during rain, when the hygrometer, sonic anemometer, and thermocouple are wet; the sensors generally take about an hour to dry out after a rain storm. Therefore, the hourly Hydra data sets for non-rainy days are selected for analysis.

The anemometers, for wind measurements 35.69, 37.52, 39.33, 41.04, 42.82, 44.66 and 48.69m above the canopy, used in the experiment employ styrofoam cups (Sheppard modified model) and are prone to stalling errors at low wind speed (less than 0.5 m s^{-1}), and over-speeding at all speeds. Estimates of this contribution to over-speeding, suggest an increase on the order of 2-5% at wind speeds around 5 m s^{-1}. The measurements of temperature and humidity above the canopy were made with aspirated, quartz crystal psychrometers manufactured by Hewlett-Packard. The measurements represent the spatial average at each level to an accuracy of 0.02 °C in temperature and 0.2g kg^{-1} in humidity. The profile data were originally obtained over 20 min intervals. Three consecutive 20 min interval profiles were used to obtain 1 h mean profiles and were analyzed for this study.

RESULTS

To determine the roughness length (z_0) and zero-plane displacement (d), we used the measured hourly momentum fluxes (τ) and the 20 min wind profiles. The iterative procedure of Robinson (1962) is used to determine z_0 and d from 200 quasi-adiabatic wind profiles. In several occasions z_0, d and τ were unrealistic when compared with other values. Such values of z_0 and d are not used to obtain their means. The mean value of 2.7 m and 27.8 m are obtained for z_0 and d, respectively. Here, d is assumed to be a well-defined aerodynamic characteristic of the surface, identical for all properties and independent of stability. Further critical analysis of z_0 and d is difficult to present in this short paper. Eqs. (2-4) can be utilized to compute β_u, β_θ and Ri from simultaneous measurements of fluxes and profiles. It is conventionally assumed that the β's represent the "shape factors", while Ri serves as a "scaling factor". This distinction suggests that a shape factor can be compared with the role of a dependent variable, the scaling factor with that of an independent variable.

Figure 1 shows experimentally determined β_u (solid curve) and β_θ (dashed curve) as a function of Ri for the second campaign data sets. The numbers beside the circles ($\pm 1\sigma$ – standard deviation) indicate the number of observations used to obtain means. Experimental data in Figure 1 are observed to be concentrated for Ri profile measurements, the variation of β_u and β_θ is strong and often erratic as shown in Figure 1. A remarkable feature of the data in Figure 1 is the very rapid deviation from the neutral profile for only slightly diabatic cases. This corresponds to a fairly large variation of the F ratio (Viswanadham, 1982 and Viswanadham *et al.,* 1987). Values of the β's generally start with near-unity values for neutral conditions and are more than unity for slightly unstable conditions. They decrease consistently with strong inversion conditions. The observed range of β_u is roughly 0.22 to 1.87 and for β_θ is -0.77 to 1.73. Throughout the diurnal period the profiles show persistent curvature over the Amazon forest. Namely, the above computed values of the shape factors (i.e., β's) ranging between -0.77 and 1.87 for the entire diurnal period represent the change in the thermal stratification between inversion and lapse conditions. This can be verified in Figure 1 where it is immediately apparent that the points disagree significantly with the semi-empirical model of Businger *et al.* (1971), because β's remain larger than unity even for positive Ri. Such "anomalous" values of β's should be analyzed very carefully in the future.

Practically all theoretical models of diabatic profile structure share one important feature. Namely, whenever they produce satisfactory results at negative and slightly positive Ri values, they appear unrealistic at larger Ri values (i.e., the empirical data fail to produce β's which approach zero). Moreover, the empirical relationships between β's and Ri seem to become erratic at Ri larger than approximately 0.1 (Figure 1). In order to show that there is little local effect, especially no significant effect of z_0 in this relation, empirical β's as a function of Ri values are also illustrated for other locations (Figure 1 in Viswanadham, 1982)

All three special cases of Eq. (5) are observed over the Amazon forest; they are given in Table 1. The theoretical lines obtained from Eq. (6) and the experimental values are presented in Figure 2. All points within this figure fall between limits $\beta_u = 0$ and $\beta_u = 2$. We selected values of Δ and δ for high Ri values (i.e., $0.03 < \mathrm{Ri} < 1$) and plotted them separately (figure omitted due to limited space) to estimate the ratio δ/Δ in Eq. (6). The experimental points for these high Ri values lie between limits $\beta_u = 0$ and $\beta_\theta = 1$ (also Figure 2). The slope (δ/Δ) of the straight line fit for these points varies reasonably between 2/3 to 3/4. The minus 2/3 and 3/4 power dependence of the F ratio on Ri (Eq. 6) is in qualitative agreement with the

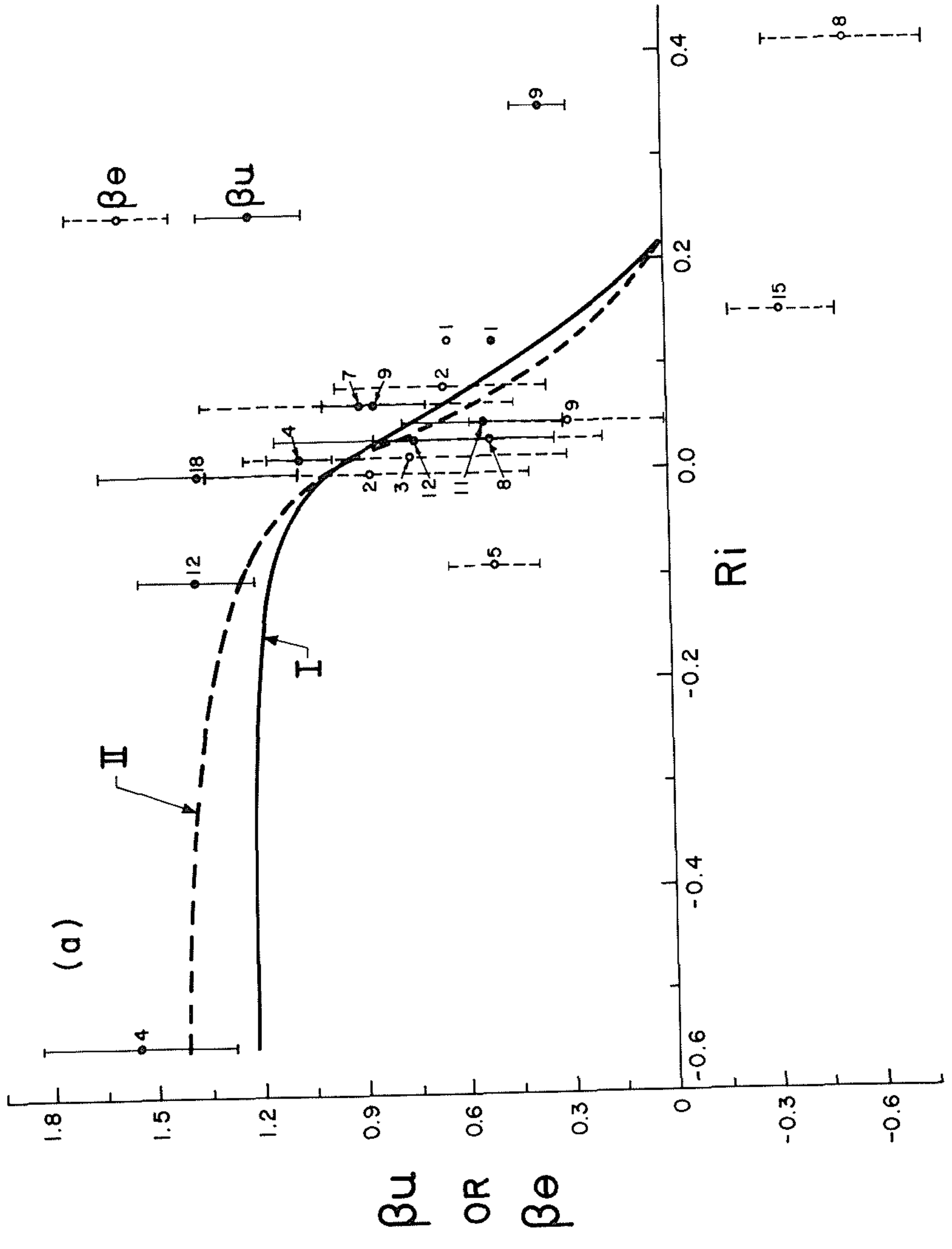

Figure 1 The Deacon number, β_u or β_θ, versus Ri for the second campaign. The theoretical curves (I-for β_u and II-for β_θ) are according to the empirical model of Businger *et al.* (1971) (See Viswanadham, 1982 for details).

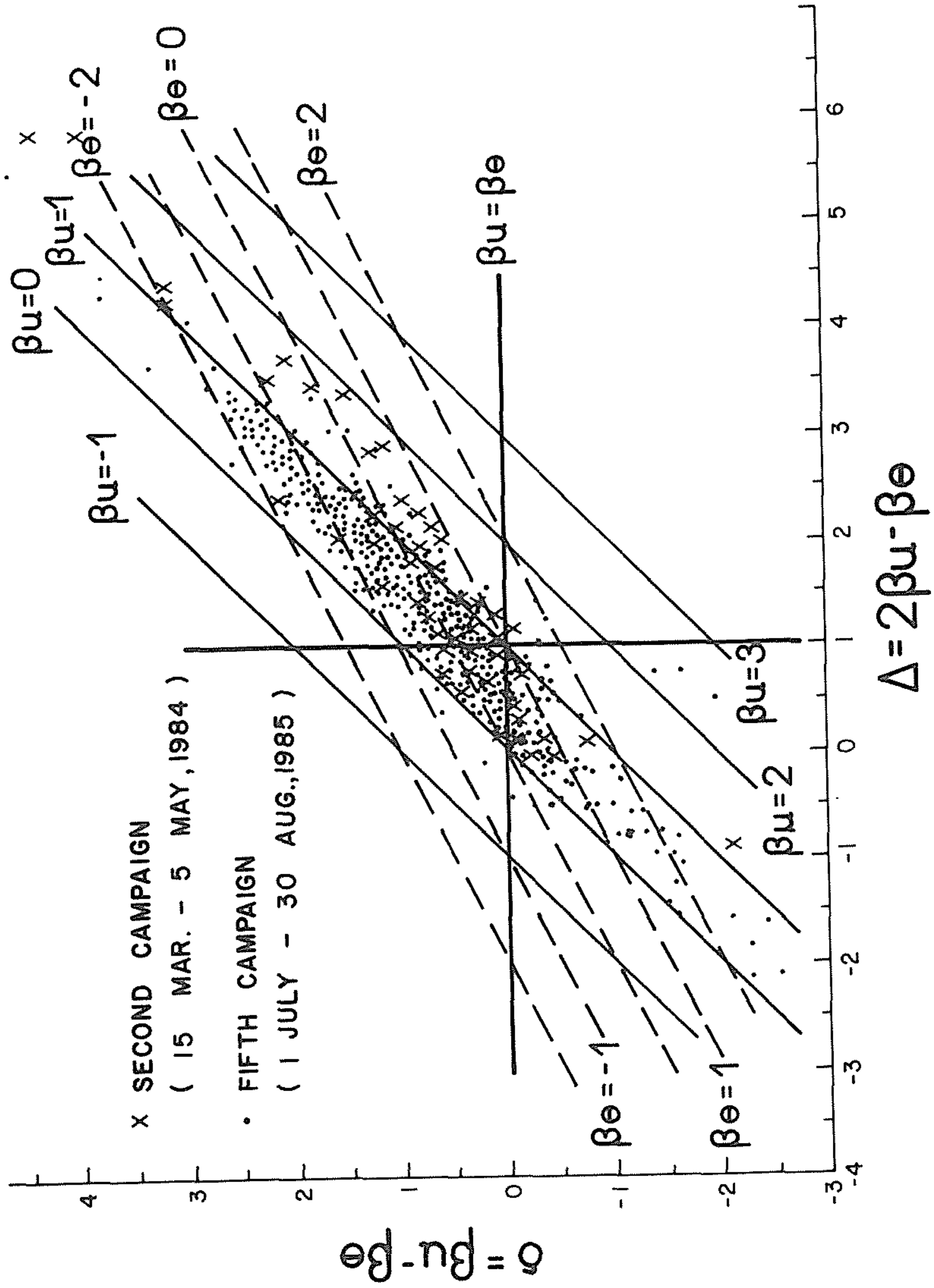

Figure 2. Relationship between $\beta_u - \beta_\theta$ and $2\beta_u - \beta_\theta$ for wind and temperature profiles. The solid lines are isolines of β_u, while the dashed lines are isolines of β_θ. The horizontal line represents the locus of $\beta_u = \beta_\theta$, while the vertical line represents the locus of $2\beta_u - \beta_\theta = 1$.

Table 1. Some selected values of β_u and β_θ from the analysis of profile data sets to illustrate three special cases of Eq. (5)

SERIAL	DATE	LOCAL TIME	Ri	β_u	β_θ
SECOND CAMPAIGN					
$2\beta_u - \beta_\theta \simeq 1$					
1	12.4.84	0500	0.024	0.405	-0.263
$2\beta_u \simeq \beta_\theta$					
1	2.4.84	1900	0.071	0.954	1.734
2	5.4.84	1700	0.005	1.293	2.598
3	6.4.84	0040	0.044	0.221	0.447
4	6.4.84	0100	0.040	0.347	0.675
5	12.4.84	2020	0.091	0.549	0.962
6	14.4.84	0100	0.018	0.409	0.898
$\beta_u \simeq \beta_\theta$					
1	4.4.84	1720	0.069	0.951	0.873
2	5.4.84	1720	0.070	1.020	1.200
3	6.4.84	0140	0.163	0.570	0.690
4	12.4.84	1640	0.071	0.912	1.095
5	13.4.84	1721	0.157	0.871	0.833
6	13.4.84	1740	0.105	1.919	1.833
7	13.4.84	2140	0.339	0.959	0.910
8	15.4.84	1520	0.004	1.270	1.337
9	15.4.84	1640	0.019	1.841	1.753
10	30.4084	2120	0.021	0.512	0.517
11	30.4.84	2300	0.020	0.490	0.493

theoretical models of Ellison (1957) and Kondo *et al.* (1978) respectively (see Eq. A11 in Viswanadham, 1982). Figure 2 (or Eq. (6)) is the basis for the conclusion that the diabatic F must be a unique valued function of the Ri when βs are a unique valued function of Ri, or vice versa. Limited space prevents further elaboration of Figure 2.

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