THE ADVECTIVE REGIMES ON THE AMAZON FOREST CANOPY

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1. INTRODUCTION

It is commonly accepted that humid tropical regions have a high radiation income and abundant precipitation so that the air is very humid and hot. It is easy to conclude that these climatic conditions generate exuberant tropical vegetation. It has long been recognized that the atmospheric and soil-vegetation systems are dynamically coupled through the physical processes which bring about the transport of thermal energy and water mass across the land surface. This phenomenon explains the importance of current knowledge regarding the micrometeorology of forests. A description of characteristics of the atmospheric turbulence in the surface layer over forest canopies is essential for understanding of the micrometeorological environment of forests. Although measurements of mean flow and turbulent fluctuations had been made in this layer (e.g., Maki, 1976; Raupach and Thom, 1981; Shuttleworth et al., 1982; Moore, 1976; Viswanadham et al., 1987; Fitzjarrald et al., 1988 and many others), the turbulence aspects including the advective conditions have not yet been studied sufficiently.

It is very difficult to calculate the advection of a tropical rain forest (Amazon forest) because some of the advective terms are not yet measurable due to the great heterogeneity of species and tree sizes. Nevertheless, Warhaft (1976) provided expressions for the vertical heat and moisture fluxes in the stratified boundary layer using two different models (Donaldson 1972; Launder 1975) for the pressure train term in the equations for the conservation of heat and moisture flux. The parameterization of Warhaft is only strictly applicable to homogeneous turbulence and we expect, at best, a qualitative view of the situation near the ground. Warhaft predicted that the eddy transfer coefficient for sensible heat (K_H) would be less than the eddy transfer coefficient for latent heat (K_W) when the sensible heat flux (Q_H) was directed downwards and the water vapor flux (Q_E) was upwards, which are the conditions within an advective inversion (Warhaft, 1976; Brost, 1979). A second possible reason is that in turbulent transport, K_H and K_W depend on the characteristics of the whole flow and not simply on local properties. Thus, we expect K_H and K_W to depend on the respective temperature and humidity profile shapes; if these are different, then differences between K_H and K_W are possible. For example, transport within forest canopies is dominated by infrequent, large eddies, which bring air down from above the canopy, where the temperature is similar to that within the canopy but humidity is lower. In these circunstances, simple K-theory is invalid and counter-gradient fluxes are observed (Denmead and Bradley, 1985; Raupach, 1987). A similar situation is possible within an advection inversion where the temperature is a maximum at same height but the humidity profile is monotonic. Limited space prevents all these discussions of our experimental results.

The present work describes the field experiments at a Ducke Reserve Forest (DRF) site (2°57'S; 59°57'W) in the Amazonian evergreen forest, Amazonas, Brazil. The main objective was to establish the relationship between eddy transfer coefficients from direct measurements of eddy fluxes of Q_H and Q_E together with simultaneous measurements of the profiles of temperature and humidity.

2. BASIC RELATIONSHIPS

The flow over a forest canopy of height h (m) exerts an influence throughout a roughness sublayer that extends considerably above height z (m) = h. At its upper limit, the roughness sublayer merges with an inertial sublayer in which the Monin-Obukhov's similarity theory can be applied.

According to the constant flux layer similarity theory (Monin and Yaglom, 1977), the eddy transfer coefficients for sensible (K_H $m^2 s^{-1}$) and latent (K_W $m^2 s^{-1}$) heats may be written in terms of the fluxes and the dimensionless profile gradients as

$$K_H = -Q_H/[\rho C_p(\partial\theta/\partial z)] = ku_*(z-d)/\phi_H \quad (1)$$

and

$$K_W = -Q_E/[\rho\lambda\,(\partial q/\partial z)] = ku_*(z-d)/\phi_W \quad (2)$$

Also, the fluxes of momentum (τ kg $m^{-1} s^{-2}$), sensible (Q_H W m^{-2}) and latent (Q_E W m^{-2}) heats in terms of eddy covariances,

$$\tau = -\rho\,\overline{u'w'} \quad \text{or} \quad u_* = (|\tau/\rho|)^{1/2} \quad (3)$$

$$Q_H = \rho C_p\,\overline{w'\theta'} \quad (4)$$

$$Q_E = \rho\lambda\,\overline{w'q'} \quad (5)$$

where ρ is the density of air (kg m^{-3}); k is von Kármán constant (taken here as 0.4); u_* is the friction velocity (m s^{-1}); θ is the mean potential temperature (K); q is the specific humidity (kg kg^{-1}); Cp is the specific heat of air (J Kg^{-1} K^{-1}); λ is the latent heat of vaporization of water (J kg^{-1}); d is the zero-plane displacement (m); ϕ_H and ϕ_W are the nondimensional shear functions for heat and water vapour, respectively, and u', w', θ' and q' are departures from means of the horizontal wind velocity, vertical wind velocity, temperature and specific humidity, respectively, and overbars denote time averages.

If we define Bowen ratios from fluxes (β_f) and gradients (β_g) as

$$\beta_f = (Cp/\lambda)\ (\overline{w'\theta'}/\overline{w'q'}) \tag{6}$$

and

$$\beta_g = (Cp/\lambda)\ (\Delta\theta\ /\ \Delta q) \tag{7}$$

where $\Delta\theta$ and Δq are measured between the same vertical heights, and finite differences have been substituted for differentials, then from Eqs. (1) and (2)

$$(K_H/K_W) = (\beta_f/\beta_g) \tag{8}$$

There are theoretical reasons why K_H may not always equal K_W. For example, buoyancy may act differently on the heat-carrying and vapor-carrying parcels of air, but this is only possible if these parcels are at least partially distinct (e.g. Launder, 1978).

The Richardson gradient number (Ri) is defined as

$$Ri = [(g/\overline{\theta})\ (\partial\theta/\partial z)]/(\partial u/\partial z)^2 \tag{9}$$

where g is the acceleration due to gravity ($m\,s^{-2}$) and $\overline{\theta}$ is the average potential temperature of the layer under consideration. The above equations can be utilized to compute ratios of eddy transfer coefficients and Ri from simultaneous measurements of fluxes and profiles over the Amazon forest.

3. 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 Amazônia (INPA), Manaus, Amazonas, Brazil.

The topography of the basin is gently undulating with valleys several tens of meters deep occuring 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 height of the trees varies from 20 to 42 m with an average height of 30 m and standard deviation of 4 m (Sá et al., 1988). 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 commom 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 Sá 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 instrumet 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 Sá 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.

All radiation instruments were mounted at a height of 45 m at the top of an aluminium scaffolding tower. Two funk-type net radiometers were used to provide the measurements of net radiation Q* (W m^{-2}). The sensitivity of these instruments is 0.85 mV/mW cm^{-2}. These were mounted perfectly level at the end of 3.5 m booms orientated approximately 30° west and 30° east of nort. With this orientation there was no possibility of tower shade interfering with the measurements. The mean value of two measurements was considered as net radiation. The measurements produced by these pairs of instruments agreed within systematic errors of 3% or less; their respective mean values were used in the analysis. All the radiometers used in this experiment have been used and recalibrated over ten years with a total change in calibration of about one per cent over this time. The data were recorded by an analog-digital interface linking system with a microcomputer (Commodore 64). The processed 20 minutes data sets from the microcomputer are saved both on a disk and a paper print out.

The digital noise in the measurements is reduced to around $1.5\,W\,m^{-2}$.

4. RESULTS

This extended abstract describes some preliminary results of the advective conditions from the Amazonia rain forest micrometeorological experiment. Several intensive periods of data collection from micrometeorological instrumentation are planned from 1983 to the next few years. Already data have been collected in seven experiments. The third experimental (13^{th} July to 31^{st}August, 1984) data sets were used to calculate the ratio K_H/K_W during advective conditions. Stable conditions over the Amazon forest canopy usually occur during early morning, afternoon and night hours, when available energy (i.e., net radiation Q*) at the canopy surface is relatively low, so that sensible and latent heat fluxes are small and thus relatively difficult to measure. However, local advection, arising from a transition from a dry to a wet surface, typically causes locally stable conditions accompanied by very large fluxes. Measurements are easier with these conditions but interpretation is complicated by the addition of another dimension. One criterion for the identification of advective influences is that Q_E/Q^* is consistenly greater than unity on an hourly basis (Oke, 1979; Viswanadham and André, 1983).

The iterative procedure of Robinson (1962) is used to determine the roughness length z_o (m) and d from 80 quasi-adiabatic wind profiles of the Amazon forest. The mean values of 3 m and 28 m are obtained for z_o and d, respectively. Twenty hourly data sets were selected using the above criterion for advection situations. Equations (1-2) or Equations (6-8) are chosen to compute the ratio K_H/K_W with the availability of the appropriate data sets for the layer 41.04 to 44.66 m above the surface. The stability parameter Ri for the same layer is obtained from Eq.(9). The results are presented in Table 1. They show that K_H/K_W vary from -1.41 to 4.03 in the stability range -0.170 to 0.287. The present results indicate that K_H/K_W is greater than unity under stable conditions and also two negative values are noticed for the ratio. Literature on the subject of transfer coefficient relationships in and above forests offers many diverse discussions. Viswanadham et al. (1987) presented a critical discussion about K_H/K_W greater than unity under stable conditions. The present results are consistent with Raupach (1979) and Viswanadham et al. (1987). The most dramatic examples of negative values of K_H/K_W are associated with countergradient heat and water vapor fluxes over the real forest canopies (Denmead and Bradley, 1985; Raupach, 1987). Even after applying corrections for the eddy correlation flux measurements, $K_H/K_W > 1$, which conflicts with theoretical predictions of Warhaft (1976). It was thus clear that equivalence of K_H and K_W under stable conditions should not be taken for granted and that relationships between transfer coefficients under an advective inversion need further investigation.

TABLE 1. The eddy transfer coefficients ratio K_H/K_W during advective conditions from the third Amazon forest experimental data set.

Serial nº	Date	Local Time Hours	Ri	K_H/K_W
1	28.7.84	0500	0.282	1.87
2	29.7.84	1800	0.068	2.22
3	30.7.84	1600	0.055	-0.29
4	31.7.84	2100	0.079	0.93
5	31.7.84	2200	0.056	1.07
6	14.8.84	1600	0.044	4.03
7	14.8.84	2100	0.053	1.27
8	20.8.84	0800	-0.170	1.14
9	20.8.84	1500	-0.094	1.67
10	20.8.84	2200	0.038	2.15
11	20.8.84	2300	0.062	1.06
12	22.8.84	0700	0.001	1.11
13	22.8.84	1500	0.061	1.54
14	22.8.84	1600	-0.003	2.11
15	22.8.84	2200	0.098	1.21
16	23.8.84	1900	0.021	0.74
17	24.8.84	0800	-0.006	1.32
18	24.8.84	1900	0.089	0.87
19	24.8.84	2100	0.016	0.55
20	25.8.84	0700	0.004	-1.41

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