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Ratios of eddy transfer coefficients over the Amazon forest

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ABSTRACT Simultaneous profile and eddy flux data gathered over the Amazon forest, Brazil, have been analyzed to find values of the nondimensional functions $\phi_{M,H,W}$ and vertical eddy diffusivities $K_{M,H,W}$ (the subscripts M, H and W represent the parameters for momentum, heat and water vapour transfer, respectively). The ratios K_H/K_M and K_H/K_W are obtained from ϕ functions. The ϕ functions and ratios of eddy diffusivities are presented over a stability (Ri=Richardson number) range of $-1.0<Ri<0.25$. The results show: (a) in quasi-neutral conditions ($-0.03<Ri<0.03$), the inferred values of ϕ_M, ϕ_H and ϕ_W are 1.28 ± 0.13, 0.53 ± 0.25 and 0.45 ± 0.15, respectively; (b) the ratios K_H/K_M, K_W/K_M and K_H/K_W are greater than unity in unstable, near neutral and slightly stable conditions; and (c) K_H/K_W is less than unity for $Ri>0.04$. To account for the anomalies in K's, a brief discussion is presented based on turbulent transport processes.

Rapport des coéfficients de transfert turbulent au-dessus de la forêt amazonienne
RESUME Des données simultannées de profils et de flux turbulents au-dessus de la forêt amazonienne, au Brésil, ont été analysées pour trouver les valeurs des fonctions non-dimensionnelles $\phi_{M,H,W}$ et des diffusivités turbulentes verticales $K_{M,H,W}$ (les indices M, H et W représentent les paramètres des transferts de moment, de chaleur et de vapeur d'eau). Les rapports K_H/K_M et K_H/K_W sont obtenus à partir des fonctions ϕ. Ces fonctions ϕ de même que les rapports de diffusivité turbulente sont présentés pour un écart de stabilité de $-1.0<Ri<0.25$ (Ri=nombre de Richardson). Les résultats montrent que: (a) sous conditions quasi-neutres ($-0.03<Ri<0.03$), les valeurs calculées de ϕ_M, ϕ_H et ϕ_W sont 1.28 ± 0.13, 0.53 ± 0.25 et 0.45 ± 0.15 respectivement; (b)les rapports K_H/K_M, K_W/K_M et K_H/K sont >1 sous conditions instables, neutres et faiblement stables; et (c) K_H/K_W est <1 quand $Ri>0.04$. Une brève discussion basée sur les processus de transfert turbulent est présentée pour expliquer les anomalies des K.

INTRODUCTION

Results from a number of field experiments, interpreted against the principles of Monin-Obukhov's similarity theory (Monin & Yaglom, 1977), have established dimensionless forms for the flux-profile relationships and for the turbulence structure, as functions of thermal stability (Viswanadham, 1982). These formulations provide a working basis for further studies in forest meteorology and other allied fields. The objective of this paper is to determine ratios of eddy transfer coefficients based on simultaneous measurements of the vertical turbulent fluxes and vertical profiles above the Amazon tropical rain forest.

The analysis makes use of simple similarity arguments suggested by Monin-Obukhov's theory for turbulent flow over uniform surfaces. From this theory, values of eddy diffusivity coefficients and their ratios are obtained. These results can be useful for the various atmospheric boundary layer models and also for the Bowen ratio/energy balance method. This study forms part of a larger project which is examining the whole question of the Amazon forest-atmosphere interaction.

THEORETICAL 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 & Yaglom, 1977), the dimensionless profile gradients for momentum, temperature and water vapour may be written as

$$\frac{k(z-D)}{S_*}\frac{\partial S}{\partial z} = \phi_{M,H,W}(\zeta), \text{ for } z > h \tag{1}$$

in which k is von Kármán's constant (=0.4) and D(m) is equal to sum of the zero-plane displacement d(m) and the roughness-length z_o(m). S may be wind speed u(m s^{-1}), potential temperature Θ(°K) and specific humidity q(kg kg^{-1}) at height z. The quantity S_* represents any one of the scaling parameters u_*, Θ_* and q_* (see Viswanadham, 1982).

Current surface-layer similarity theory predicts that the non-dimensional shear functions ϕ_M, ϕ_H and ϕ_W depend only on the stability parameter ζ =(z-D)/L. L(m) is Monin-Obukhov length. The quantities u_*, Θ_*, q_* and L are assumed to specify the dynamics of the flow field.

Equation (1) implies that the eddy diffusivities K_M (m^2s^{-1}), K_H (m^2s^{-1}) and K_W (m^2s^{-1}) are given by

$$K_{M,H,W} = \frac{k\ u_*\ (z - D)}{\phi_{M,H,W}} \tag{2}$$

Ratios of the eddy diffusivities are

$$\frac{K_H}{K_M} = \frac{\phi_M}{\phi_H} = F_1\ (\zeta);\ \frac{K_H}{K_W} = \frac{\phi_W}{\phi_H} = F_2\ (\zeta) \tag{3a,b}$$

The similarity theory further predicts that the Richardson number Ri and the flux Richardson number R_f defined as

$$Ri = (g/\bar{\Theta})\ \frac{(\partial\Theta/\partial z)}{(\partial u/\partial z)^2} = \frac{K_M}{K_H} \cdot \frac{\zeta}{\phi_M} = \frac{\phi_H\ \zeta}{\phi_M^{\ 2}}\ F_3\ (\zeta) \tag{4}$$

$$R_f = \frac{K_H}{K_M}\ Ri = \frac{\zeta}{\phi_M} = F_4\ (\zeta) \tag{5}$$

are universal functions of ζ. $\bar{\Theta}$ is the average potential temperature of the layer under consideration. Universal functions $\phi(\zeta)$, F_i (ζ), etc., cannot be predicted by the similarity theory along. Therefore, the theory must necessarily be supplemented by experimental work (see Viswanadham, 1982).

To determine the shear functions (ϕ's) experimentally, it is necessary to measure independently the fluxes of momentum, heat and water vapour and the gradients of u, Θ and q, and also to make some determination of d. Here, d is assumed to be a well-defined aerodynamic characteristic of the surface, identical for all properties and independent of stability. The iterative procedure of Robinson (1962) is used to determine z_o 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. Equations (1-4) can be utilized to compute $\phi_{M,H,W}$, $K_{M,H,W}$, ratios of eddy diffusivities and Ri from simultaneous measurements of fluxes and profiles over the Amazon forest.

EXPERIMENTAL SITE AND DATA SETS

The field work took place in the tropical evergreen forests of the Amazonas basin, Brazil. The measurements were made from a 45 m scaffolding tower at (2°57'S; 59°57'W), situated in the Ducke Reserve Forest (DRF), 26 km from Torquato Tapajos Highway, Manaus, Amazonas. The DRF site is 84 m above mean sea level. The DRF belongs to the Instituto Nacional de Pesquisas da Amazonia (INPA), Manaus, Amazonas, Brazil. The tower has fetches of undisturbed forest extending more than ten kilometers in most directions. A common intuitive rule amongst micrometeorologists is for a height/fetch ratio of 1/100 to 1/500. This condition is satisfied by the present observational site.

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, UK. The instrument was mounted on a pole above the tower at a height of 48.4 m. 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 48.69 m above the canopy, used in the experiment employ styrofoam cups (Casella model) and are prone to stalling errors at low wind speed (less than 0.5 m s^{-1}), and overspeeding at all speeds. Estimates of this contribution to overspeeding, 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

Fig.1 shows experimentally determined ϕ functions above the Amazon forest, as calculated from Equation (1) using measured fluxes and average gradients at geometric mean height for the 41.04 to 44.66 m layer. In Table 1 some selected values of K's and their ratios are presented from low negative Ri value to high stability. The numbers on the vertical bars ($\pm 1\sigma$ - standard deviation) indicate the number of observations used to obtain means. Fig.1 reveals considerably less deviations for Ri<0 and more for Ri>0. A quite good trend is noted for all the three ϕ functions. This pattern might be expected since both the gradients and fluxes are normally strong under highly unstable conditions, while low under stable conditions. The likelihood of high accuracy of the ϕ ratios is thus much better as free convection is approached. The present value of $\phi_M(0) = 1.28$ approximately compare with 1.11 of Garratt (1978). Our value of $\phi_H(0) = 0.53$ agrees well with 0.53 of Garratt (1978). Finally, our value of $\phi_W(0) = 0.45$ is half of 0.885 of Pruitt *et al.* (1973). From our data it is difficult to make a firm statement concerning which formulation of ϕ_M, ϕ_H and ϕ_W is to be preferred.

Literature on the subject of transfer coefficient relationships offers many diverse opinions. Various studies suggest that the ratios of K_H/K_M, K_W/K_M and K_H/K_W are significantly greater than 1.0 for quasi-neutral conditions (Pruitt *et al.*, 1973). The present results also give considerable support to this conclusion. A number of studies have shown a very significant increase in these ratios with increasing instability. For example, Dyer & Hicks (1979) show $K_H/K_M>2$ at $z/L = -1.0$. It is obvious then, that the Amazon results indicate somewhat greater values of these ratios for unstable conditions (Fig.2 and Table 1).

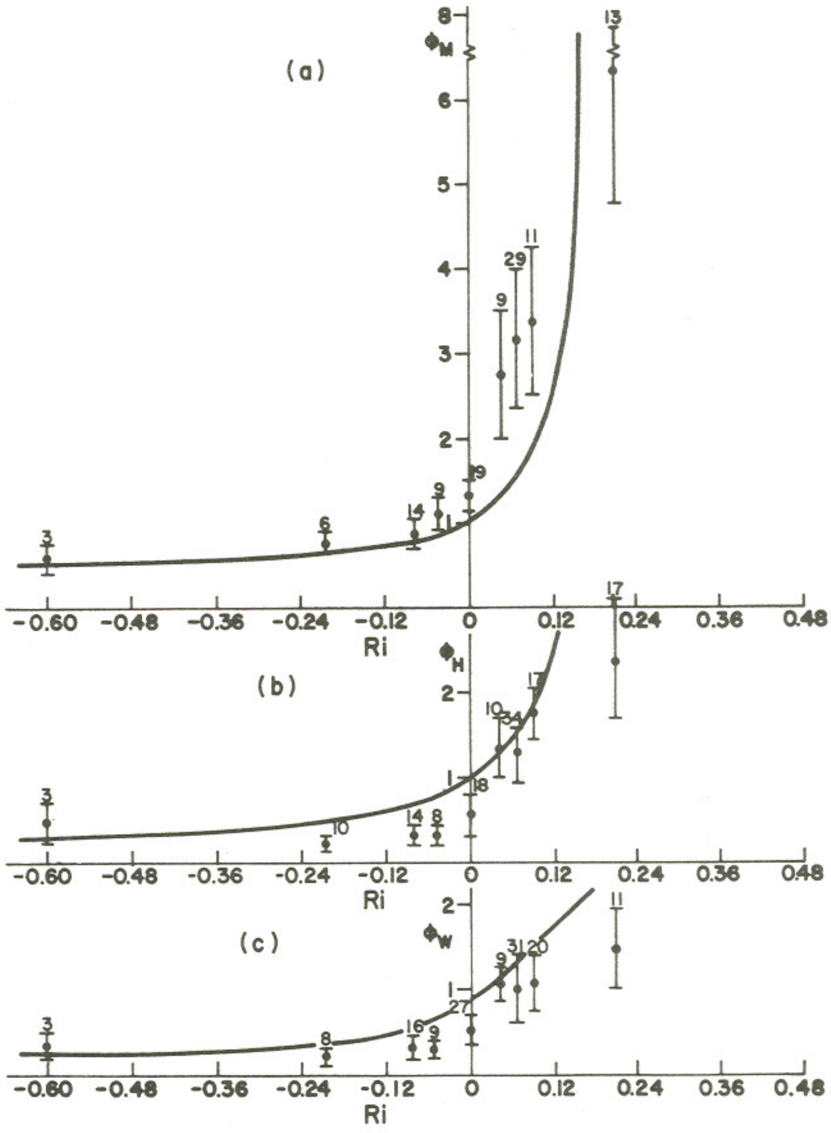

FIG.1 Average values of (a) ϕ_M, (b) ϕ_H and (c) ϕ_W plotted against Ri. The smooth solid curves in (a) and (b) are obtained according to the formulae of the Dyer & Hicks (1970) for Ri<0 and Webb (1970) for Ri>0 (see Viswanadham, 1982), and in (c) is due to Pruitt et al. *(1973).*

TABLE 1 Some selected values of K_M, K_H, K_W and their ratios over the Amazon forest

Serial No.	Data	Local Time(h)	Ri	K_M (m^2s^{-1})	K_H (m^2s^{-1})	K_W (m^2s^{-1})	K_H/K_M	K_H/K_W
1	19/8/84	1000	-0.656	1.896	7.108	6.753	3.75	1.05
2	25/8/84	0800	-0.376	2.317	3.519	3.845	1.52	0.92
3	20/8/84	0800	-0.170	1.290	5.573	4.905	4.32	1.14
4	15/8/84	1400	-0.136	1.643	6.783	5.155	4.13	1.32
5	20/8/84	1500	-0.094	1.612	7.630	4.781	4.73	1.60
6	11/8/84	1200	-0.068	2.447	5.611	5.559	2.29	1.01
7	09/8/84	0800	-0.053	1.705	4.487	3.521	2.63	1.27
8	23/8/84	1000	-0.040	2.199	7.967	10.549	3.62	0.75
9	11/8/84	1000	-0.030	2.459	7.788	7.200	3.17	1.08
10	22/8/84	0700	-0.005	0.888	3.147	2.982	3.54	1.06
11	11/8/84	0600	0.041	0.274	0.570	0.986	2.08	0.58
12	23/8/84	0300	0.047	0.336	0.797	1.356	2.37	0.59
13	29/8/84	1700	0.052	0.600	1.166	1.824	1.94	0.64
14	24/8/84	0400	0.062	0.259	0.692	1.134	2.67	0.61
15	24/8/84	0300	0.065	0.206	0.596	0.863	2.89	0.69
16	01/8/84	0000	0.073	0.344	0.631	0.863	1.83	0.73
17	25/8/84	0100	0.078	0.170	0.490	0.739	2.88	0.66
18	31/7/84	2100	0.079	0.169	0.372	0.419	2.20	0.89
19	24/8/84	1900	0.089	0.194	0.528	0.637	2.72	0.83
20	29/7/84	2000	0.091	0.170	0.544	0.709	3.20	0.77
21	21/8/84	1800	0.100	0.197	0.370	0.472	1.88	0.78
22	24/8/84	0200	0.114	0.130	0.305	0.440	2.35	0.69

The results also do not show a similar trend to the published literature for stable conditions. Fig.2 and Table 1 show that K_H/K_M and K_W/K_M are greater than unity for Ri>0, whereas K_H/K_W is less than unity for Ri>0.04. The ratio K_H/K_M is equal to 1.68 ± 0.49 at Ri=0.21 in comparison with a unit value of Webb (1970). This is probably due to the different level of the atmosphere observed. The investigators cited above (e.g. Webb, 1970) made observations in the surface layer, mainly within a few meters of the ground surface; while the present observations were made in the 41.04-44.66 m layer above a forest. Supposedly, the most probably reason for this difference in the surface layer and the layer above the forest is the ground effect on the pressure fluctuation field in the atmospheric boundary layer, as indicated by Gibson & Launder (1978). That is, the pressure contributes to correlations which appear in the transport equations for Reynolds stress and heat flux, so that turbulent transport processes are affected not only by the stratification but also by the modification of the fluctuating pressure field due to the presence of a wall (i.e. forest). The present results (Fig.2) are consistent with Gibson & Launder (1978 -their Fig.4a, p.506).

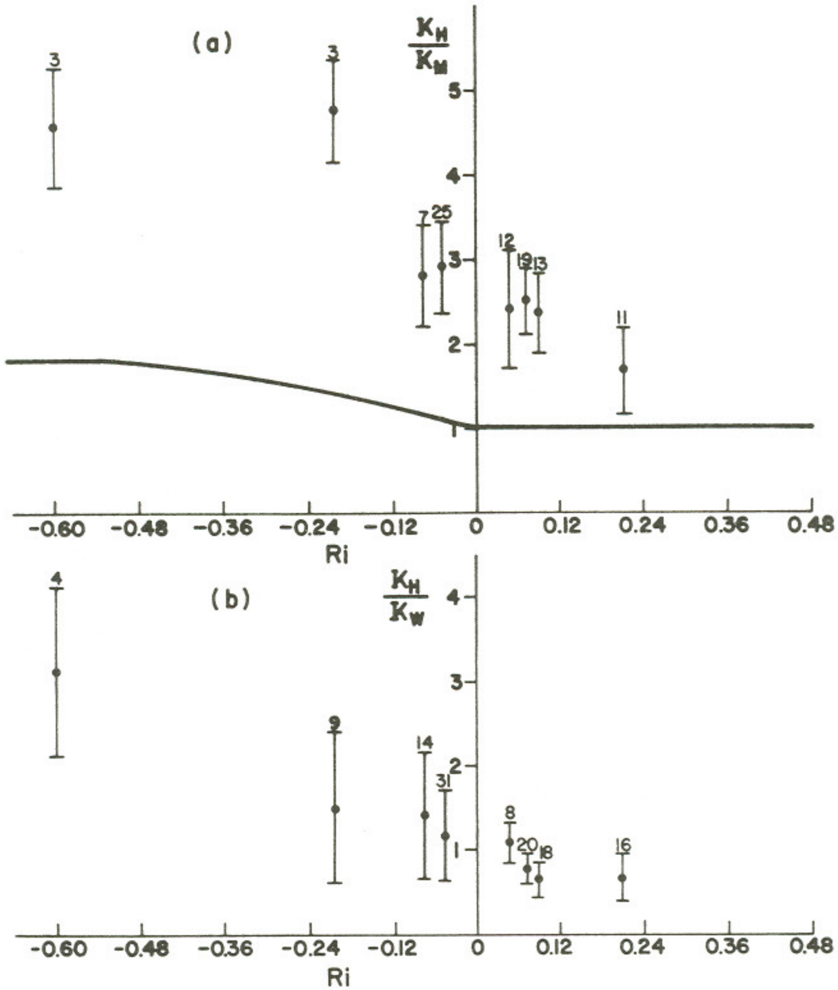

FIG.2 Variation of (a) K_H/K_M and (b) K_H/K_W with stability. The smooth solid curve in (a) is drawn according to the formulae of Dyer & Hicks (1970) for Ri<0 and webb (1970) for Ri>0 (see Viswanadham, 1982).

The examples on free turbulent flows have shown that the real phenomena can be described in an excellent way by the use of different semi-empirical hypotheses for turbulent stresses. Thom *et al.* (1975) have pointed out that there are two mechanisms (i.e. wake diffusion and thermal seeding) which could possibly operate to increase the eddy diffusivity close to aerodynamically rough surface to values substantially in excess of those based on the Prandtl-Kármán mixing length theory. A suitable starting point for such a discussion is the observation that equality of turbulent diffusivities for momentum and heat (or other properties) is not a reasonable consideration in general. Since the mechanism for the transfer of momentum and heat are not identical the values of K_M and

K_H are, generally speaking, different. In formulating the Prandtl's mixing-length expression for the eddy shearing stress it has been assumed that momentum is a conservative transferable property. This implies that the pressure fluctuations, which are by no means negligible in a turbulent fluid, do not affect the mean transfer of momentum. This is not likely to be true in general. The action of pressure forces enables a vertically migrating air parcel to exchange momentum with its surroundings more quickly than other properties, causing momentum mixing-lengths to be smaller than property mixing-lengths. This point is made by Taylor (1932), who also showed how Prandtl mixing-length theory ignores it and gives rise to the widespread assumption that $K_M = K_H = K_W$ in quasi-neutral conditions (Monin & Yaglom, 1977; p. 370; Raupach, 1979).

Taylor (1932) showed that in a strictly two-dimensional turbulence, one component of vorticity is conserved. Therefore, there are two situations where pronounced inequalities between K_H and K_M are well-known to occur. First, Thom *et al.* (1975) postulate a similarity between the heated cylinder wake and the forest situation, naming their proposed K_H - augmenting mechanism 'wake diffusion'. Schlichting (1968, p. 704) reports that in the wake behind a row of heated bars, the temperature profile is 'wider' than the velocity profile (e.g. Fage & Falkner in an appendix to Taylor, 1932) to an extent implying that K_H is roughly twice K_M (Monin & Yaglom, 1977; p. 370). This supports Taylor's (1932) vorticity transfer hypothesis rather than momentum transfer theory. The second is in the unstable boundary layer over a heated surface, where convective activity causes vertical motions to be relatively larger than in a neutral boundary layer. Thom *et al.* (1975) have suggested that free convection thermals of characteristic dimension z_o could originate within a vegetative canopy where Ri is relatively larger (and negative) and emerge into the region of turbulent, boundary-layer flow above, where the additional mixing generated would serve to enhance K and reduce profile gradients. The existence of such plumes, with cross-sections of up to a few z_o has been qualitatively demonstrated by the use of smoke trails (Oliver, 1973). So, these mechanisms may be contributory and the buoyant convection effects are largely responsible for the anomaly.

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REFERENCES

Dyer, A.J. & Hicks, B.B. (1970) Flux-gradient relationships in the constant flux layer. *Quart. J. Rey. Met. Soc.* 96, 715-721.

Garratt, J.R. (1978) Flux profile relations above tall vegetation. *Quart. J. Roy. Met. Soc.* 104, 199-211.

Gibson, M.M. & Launder, B.E. (1978) Ground affects on pressure fluctuations in the atmospheric boundary layer. *J. Fluid Mech.* 86, Part 3, 491-511.

Monin, A.S. & Yaglom, A.M. (1977) Statistical fluid mechanics: Mechanics of turbulence I. MIT Press, Cambridge, Mass., USA.

Oliver, H.R. (1973) Smoke trails in pine forest. *Weather* 28, 345-347.

Pruitt, W.O., Morgan, D. & Lourence, F.J. (1973) Momentum and mass transfers in the surface layer. *Quart. J. Roy. Met. Soc.* 99, 370-386.

Raupach, M.R. (1979) Anomalies in flux-gradient relationships over forest. *Bound.-Layer Met.* 16, 467-486.

Robinson, S.M. (1962) Computing wind profile parameters. *J. Atmos. Sci.* 19, 189-190.

Schlichting, H. (1968) *Boundary-layer Theory.* McGraw-Hill Book Co., New York.

Taylor, G.I. (1932) The transport of vorticity and heat through fluids in turbulent motion. *Proc. Roy. Soc.* A 135, 695-705.

Thom, A.S., Stewart, J.B., Oliver, H.R. & Gash, J.H. (1975) Comparison of aerodynamic and energy budget estimates of fluxes over a pine forest. *Quart. J. Roy. Met. Soc.* 97, 414-428.

Viswanadham, Y. (1982) Examination of the empirical flux-profile models in the atmospheric surface boundary layer. *Bound.-Layer Met.* 22, 61-77.

Webb, E.K. (1970) Profile relationships: The log-linear range and extension to strong stability. *Quart. J. Roy. Met. Soc.* 96, 67-90.