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Energy balance and the Priestley-Taylor parameter for forested areas in the Amazon region[1]

Balanço de energia e o parâmetro de Priestley-Taylor em áreas florestadas na Amazônia

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Abstract *- Energy balance of two forested areas in the Amazon region was measured during the ABRACOS project. One site was near Ji-Paraná, Rondônia, Brazil, in the Reserva Jaru, and other was south of Marabá, Pará, in the Reserva Vale do Rio Doce. Hourly change in canopy heat storage (S) was determined as residue of the energy budget equation with direct measurements of above canopy net radiation (Qn), latent (LE) and sensible heat (H), and soil heat flux (G). On average, LE converted about 70% of Qn. It was found that S cannot be discarded from the budget, but that G was negligible for the Amazon forest. Hourly change in S was found to be determined by the corresponding change in Qn. The direct relationship between S and Qn showed a large spread of the points; however, the assumption of S = 0.1 Qn resulted in good performance of the Priestley-Taylor (P-T) model. The P-T α parameter was affected positively by H but negatively by S; and the combined effect (H + S) had the same tendency as that determined by H independently. Negative S values enhances the above canopy LE, resulting in large α values, and it is sometimes confounded with the occurrence of advection. The relationship between α and H found for the forest did not differ significantly from that previously described for grass, which was then incorporated in the P-T model, resulting in reliable estimates of evapotranspiration. Similarly, the VISWANADHAM et al. (1992) parameterization of the P-T model gave also good estimates of LE.*

Key words: *canopy heat storage, evapotranspiration, net radiation, sensible heat flux.*

Resumo *- Em duas áreas florestadas da região amazônica, Reserva Jaru (Ji-Paraná, Rondônia) e Reserva Vale do Rio Doce (Marabá, Pará), o balanço de energia foi medido durante o projeto ABRACOS. A variação horária da energia armazenada pelo dossel vegetativo (S) foi determinada como resíduo do balanço de energia com medidas diretas de saldo de radiação (Qn), calor latente (LE), e calor sensível (H) acima do dossel, e do fluxo de calor no solo (G). Em média, LE resultou da conversão de 70% de Qn. Os valores encontrados indicam que S não pode ser descartada do balanço, mas que G é insignificante para a floresta amazônica. A variação horária de S apresentou relação linear positiva com a variação correspondente em Qn. A relação direta de S com Qn mostrou grande espalhamento nos pontos; no entanto, a premissa de que S = 0,1 Qn resultou em boa performance de estimativa de LE pelo modelo de Priestley-Taylor (P-T). O parâmetro α de P-T foi afetado positivamente por H, mas negativamente por S, e o efeito combinado (H + S) mostrou a mesma tendência encontrada independentemente para H. Valores negativos de S resultam em aumento de LE acima do dossel vegetativo, resultando em valores elevados de α, e isto é muitas vezes confundido com ocorrência de advecção. A relação de α com H encontrada para a floresta não diferiu significativamente daquela descrita anteriormente para gramado, e assim foi incorporada no modelo de P-T resultando em estimativas confiáveis de LE. De modo semelhante, a parametrização proposta por VISWANADHAM et al. (1992) também resultou em boas estimativas de LE.*

Palavras-chave: *energia armazenada no dossel, evapotranspiração, saldo de radiação, fluxo de calor sensível.*

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Introduction

The micrometeorology of forests is always difficult in many aspects. Aerodynamically, the taller and rougher vegetation interacts more strongly with the atmosphere (GARRATT, 1978), and RAUPACH (1979) detected anomalies in the flux-gradient relationship very close to the canopy top. This fact makes similarity analysis questionable just above the forest (FITZJARRALD et al., 1988), introducing unreliable estimation of sensible, and latent heat fluxes (RAUPACH, 1979; VISWANADHAM et al., 1990).

Energetically, the large biomass and volume of air trapped by the canopy poses difficulties to the energy balance methods for estimating heat fluxes. As an approximation, a forest can be represented by a box of large volume, being its depth determined by the height of the trees. Its energy balance is determined primarily through the top face of the box since the large biomass restricts the energy exchange at the bottom face. Even under advective conditions the exchange of energy is through the upper face. In terms of flux densities, the energy balance of such box can be expressed as

$$Qn = LE + H + G + P + S \qquad (1)$$

being Qn the net radiation, LE the latent heat, H the sensible heat, G the soil heat, P the net photosynthetic energy, and S the change in canopy heat storage. The canopy storage term represents the sensible and latent heat stored in the canopy air, and sensible heat stored in the vegetation (THOM, 1975). For simplicity, some authors include also the soil heat in the storage term (JARVIS et al., 1976; McCAUGHEY, 1985; McCAUGHEY & SAXTON, 1988).
Change in canopy heat storage represents gain or loss of stored energy and for the Amazonian forest it can exceed 10% of the net radiation (MOORE & FISCH, 1986), sometimes it is comparable to the sensible heat flux (FITZJARRALD et al., 1988; ASBY, 1999). Therefore, S cannot be neglected from the energy balance equation of forests (SAXTON & McCAUGHEY, 1988), mainly on short time scales (i.e., minutes, or hours).

Usually, the energy balance is used to study the partitioning of the available energy into the latent and the sensible heat fluxes. A very simple way to estimate LE is by the PRIESTLEY & TAYLOR (1972) approach:

$$LE = \alpha\, [s / (s + \gamma)]\, (Qn - G) \qquad (2)$$

being α an empirical coefficient which accounts for the aerodynamic (or adiabatic) contribution to the evapotranspiration process; s the slope of the saturation vapor pressure-temperature curve at the corresponding air temperature; and γ the psychrometric coefficient (assumed constant). Experimental results with shorter, smoother vegetation grown with plenty of soil water indicate a mean value for α in the range 1.2 to 1.3 for daily estimates. However, substantially smaller α values have been reported for forests, or 1.05 by McNAUGHTON & BLACK (1973) in a Douglas fir (Haney, BC, Canada), 0.72 ± 0.07 by SHUTTLEWORTH & CALDER (1979) for both Spruce (Plynlimon, Wales) and Scots Pine (Norfolk, England), and 1.03 ± 0.13 by VISWANADHAM et al. (1991) at the Reserva Ducke (Manaus, Brazil) in the Amazon. SHUTTLEWORTH & CALDER (1979) have even questioned its applicability for this type of vegetation, warning against its indiscriminate use with a constant α.

One objective of this work is to investigate the energy balance and the effect posed upon the Priestley-Taylor parameter by the change in the canopy heat storage, at the hourly time scale, in two areas of the Amazon forest. It also explores the opportunity to test two empirical approaches to estimate the latent heat flux for those areas using the Priestley-Taylor model. One approach was proposed by VISWANADHAM et al. (1992) from previous experiment in the Reserva Ducke forest (near Manaus) which gave a constant $\alpha = 0.93$, if it is assumed that G = 0.1 Qn. The other, is a statistical linear fit obtained by PEREIRA & VILLA NOVA (1992), for the hourly variation of α as a function of the sensible heat flux H, but for short and smooth vegetation, and the idea is to check its suitability for tall and rough vegetation such as the Amazon forest.

Material and methods

Data for the analysis were obtained from energy balance measurements performed in two sites of the Amazon forest during the ABRACOS project described in GASH et al. (1996). One site was inside the Reserva Jaru, about 80 km northeast of Ji-Paraná, Rondônia (10° 5' S, 61° 55' W, 120 m), where the average tree height was 33 m. The other site was at the Reserva Vale do Rio Doce, some 50 km south of Marabá, Pará (5° 45' S, 62° 22' W, 150 m), with mean canopy height around 25 m. Turbulent flux measurement instrumentation (eddy correlation system Hydra, Institute of Hydrology, UK) and an automatic weather station were mounted at the top of a 52 m scaffolding tower in both sites. The Hydra system is described by SHUTTLEWORTH et al. (1984) and WRIGHT et al. (1992), and it gave independent measurements of latent and sensible heat fluxes. Net all-wave radiation was also measured at the top of the tower by a REBS Q6 sensor. Soil heat flux was measured by a Thornthwaite flux plate (model 610). For this study all data were averaged hourly. Data here analyzed excluded those from rainfall hours and also those for the next 3 hours after a rain because the sensors do not perform well under that condition (SHUTTLEWORTH et al., 1984; VISWANADHAM et al., 1991).

The parameter α was determined by equation (2) using the measured fluxes. For short vegetation (grass) the hourly variation in α can be described by the empirical equation $\alpha = 1.33 + 0.00278$ H found by PEREIRA & VILLA NOVA (1992), and it was here tested against the "measured" α to check its suitability for taller and rougher vegetation. The empirical equation $LE = 0.93\,[s / (s + \gamma)]\,(0.9\,Qn) + 20$ determined by VISWANADHAM et al. (1992) for the Reserva Ducke forest was also tested against the hourly measured latent heat flux (W m^{-2}). The 0.9 Qn indicates that 10% of Qn went into the storage term.

Results and discussion

It is well documented that the latent heat flux over tropical rain forests is the second largest component of the energy balance during daytime. Results from independent experiments in the Amazon forest show that, in many time scales, the latent heat flux uses over 70% of the net radiation (SHUTTLEWORTH et al., 1984; VISWANADHAM et al., 1990), and this figure was confirmed here with the overall correlation given by LE = 0.71 Qn (r^2 = 0.8824, n = 1003) with a standard deviation of ± 39.8 W m^{2}.

An example of the hourly variation of the energy balance components is shown in Figure 1, for two selected days, at the Reserva Jaru site. As expected for this kind of vegetation, the soil heat flux was negligible throughout the day, and as such it can be discarded from the analysis without introduction of significant errors. For the sake of comparing the relative contribution of each flux along the day, the lines representing the sensible and the latent heat fluxes are shown as –H and –LE in this figure. For several hours, the change in the storage term (S) was larger than H showing that it has indeed to be considered in the energy balance of the Amazon forest. Large values for S (in the range of ± 100 W m^{-2}) was also detected by MOORE & FISCH (1986) at the Amazon forest (Reserva Ducke), and by KELLIHER et al. (1992), in a New Zealand broad-leaved forest. The relationship between S and Qn is not well defined for the Amazon forest sites (Figure 2). Only as a reference, the 10% line was drawn through the cloud of points, since this value is implicit in the VISWANADHAM et al. (1992) approach. It should

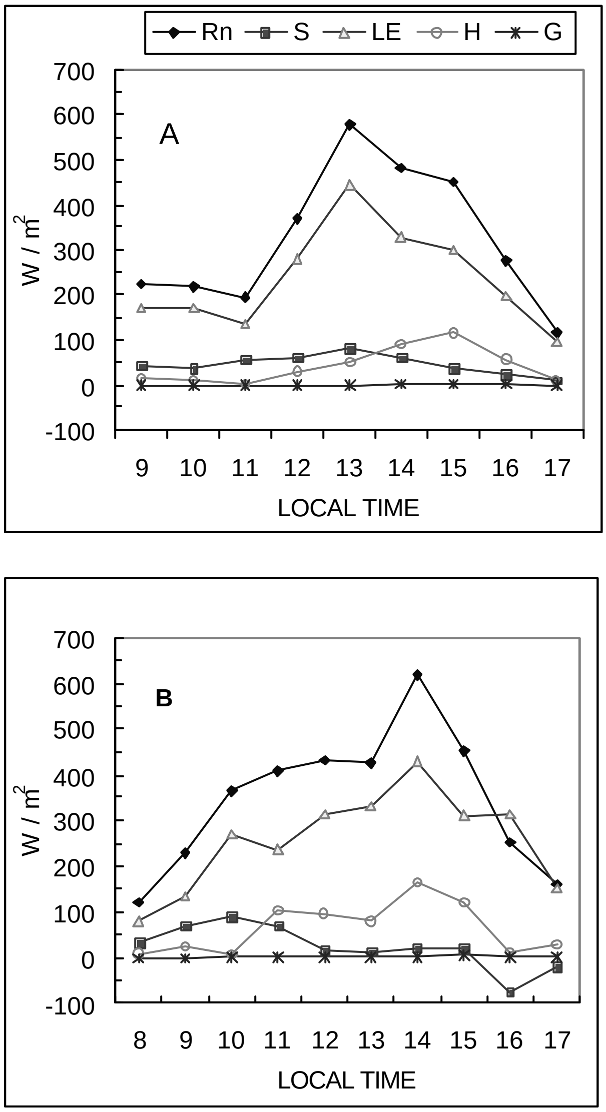

Figure 1. Hourly variation of the energy balance components at the Reserva Jaru (A, 10/8/1992; B, 20/9/1992).

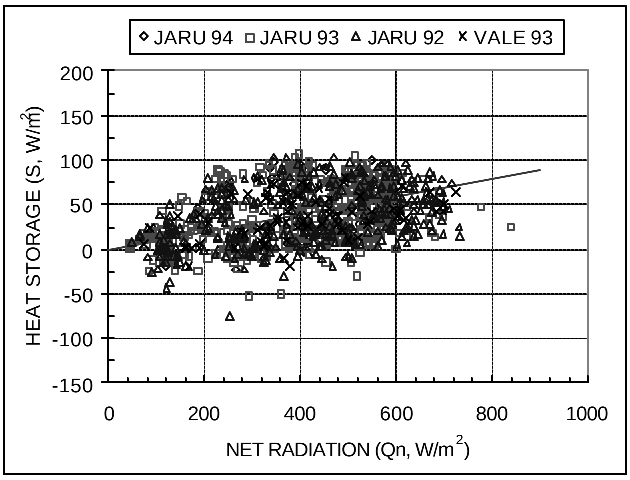

Figure 2. Relationship between the change in the forest heat storage (S) and the above canopy net radiation (Qn). The straight line represents S = 0.1 Qn.

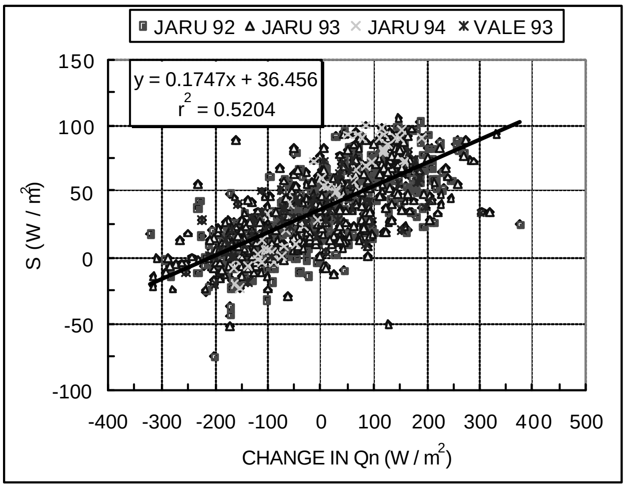

Figure 3. Relationship between the change in the forest heat storage (S) and the change of the above canopy net radiation (ΔQn).

be mentioned that S was here determined as a residue of the energy balance equation, and as such it incorporates all the errors associated with the measurements of the other terms of the equation, being its uncertainty unknown. Consequently, the large spread in the relationship can be attributed mostly to the uncertainty of the S values.

Hourly change in canopy heat storage S was found to be associated with the change in above canopy net radiation ($\Delta Qn = Qn_t - Qn_{t-1}$), and Figure 3 shows a positive linear regression with S = 0.1748 ΔQn + 36.439 (r^2 = 0.5207; n = 876). In general, large negative ΔQn values occurred mostly in late afternoon hours, when the radiant energy input was naturally decreasing. Large positive values were detected between 10 am and 2 pm, hours of maximum radiation input. In both situations the presence of clouds was the determinant factor of sudden changes in Qn. The presence of highly convective cumulus clouds can result in either large negative or large positive ΔQn values. Negative values are associated with their shades, and the positive changes are determined by the sudden burst of radiation reflected downwards by their brilliant walls, which increases substantially the input of solar radiation. Most of the points falling outside of an 'acceptable' spread around the fitted line occurred mainly late in the afternoon hours, near the sunset, and might be due to the above discussed unreliability in the computation of S.

One important aspect is to check the impact S might have upon α. For the Amazon forest, MOORE & FISCH (1986) estimated that about 70% of S is spent to increase latent and sensible heat of the canopy air. Figure 4 shows that positive values of S, or increase in the trapped energy, induced a decrease in α because the above canopy latent heat flux at that time does not take into account the corresponding latent heat stored in the canopy air. Therefore, the above canopy latent heat flux is less than the overall conversion of the net radiation into latent heat, and here it resulted in α values as low as 0.65. Conversely, as the canopy air enthalpy increases it becomes more bouyant and more likely to be expelled resulting in

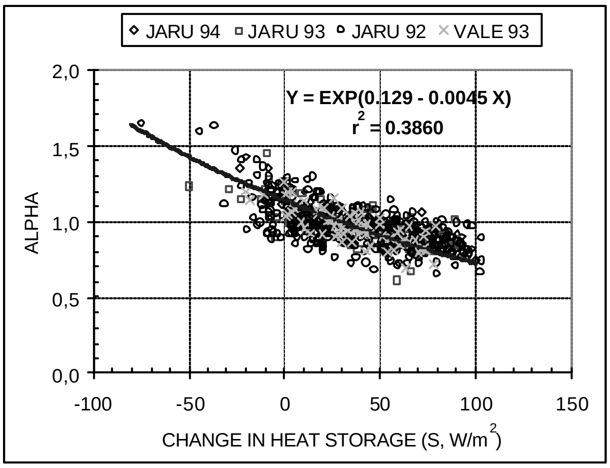

Figure 4. Relationship between the Priestley-Taylor α given by the measured fluxes and the change in canopy heat storage (S). The fitted line is α = EXP(0.129 – 0.0045 S).

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negative S. Consequently, in that condition the above canopy latent heat flux is enhanced by the canopy latent heat, thus erroneously representing a larger proportion of the net radiation conversion, and in this work it resulted in larger values of α (> 1.6). It can be inferred that sometimes the larger above forest canopy latent heat flux is wrongly believed to be caused by advection of sensible heat.

The empirical relationship between α and the sensible heat flux H (α = 1.33 + 0.00278 H) found for short grass field by PEREIRA & VILLA NOVA (1992), did not differ significantly from the fitted α = 1.245 + 0.0023 H (r^2 = 0.7580; n = 1003) shown in Figure 5. The grass function had a tendency to overpredict α when H was in the range between –20 W m^{-2} and – 80 W m^{-2}, but for H values outside this range the prediction can be considered as good. This is an apparent indication that the dependence of α on H is not accidental. The combined effect of the sensible heat flux (H) and the change in heat storage (S) on α is shown in Figure 6. The tendency was about the same observed for the independent effect of H, with the same slope but a smaller interception coefficient, or α = 1.143 + 0.002 (S + H), with r^2 = 0.6422 (n = 1003).

To further test the applicability of the α function determined by PEREIRA & VILLA NOVA (1992), the latent heat flux was estimated through the equation LE = (1.33 + 0.00278 H) [s / (s + γ)] (0.9 Qn), here called “modified Priestley-Taylor (MPT)”, assuming S = 0.1 Qn, as proposed by VISWANDHAM et al. (1992). The use of this assumption for S allows comparison of performance of the two approachs (variable versus fixed α values). The results show that the estimatives with the MPT did not differ significantly from the measured values, with the points falling along the perfect fit line (1:1), having a standard deviation of ± 27.3 W m^{-2} and r^2 = 0.9690 (Figure 7).

Similar results were obtained with the parameterization proposed by VISWANADHAM et

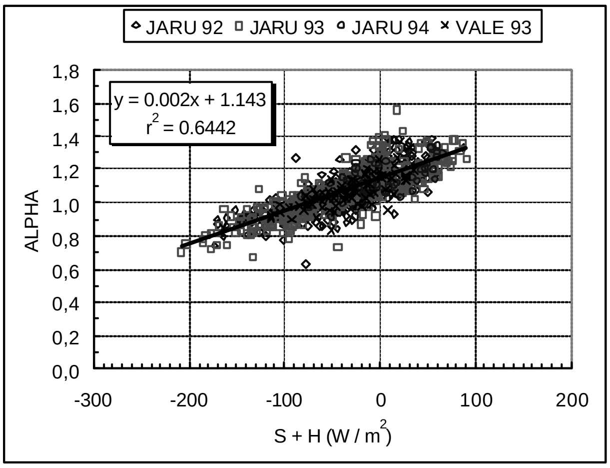

Figure 6. Relationship between α and the summation S + H.

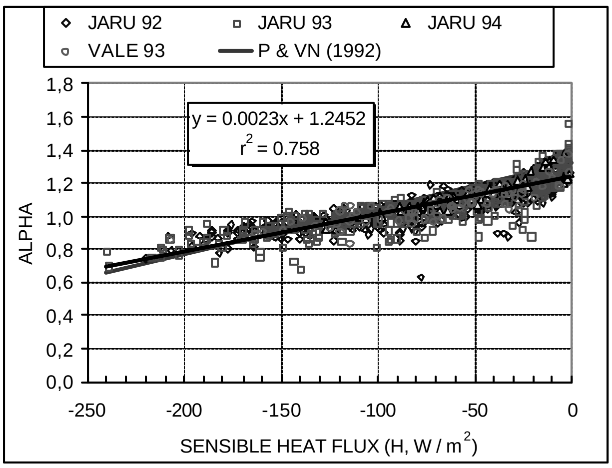

Figure 5. Relationship between α and the sensible heat flux (H) above the canopy. P & VN (1992) line is the PEREIRA & VILLA NOVA (1992) relationship for α.

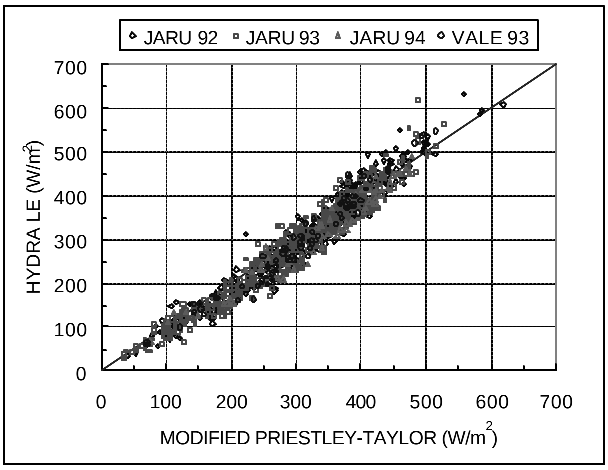

Figure 7. Relationship between measured and estimated LE, using the modified Priestley-Taylor model with variable α given by PEREIRA &VILLA NOVA (1992).

al. (1992), or LE = 0.93 [s / (s + γ)] (0.9 Qn) + 20, with the points falling also along the 1:1 line, but with a larger spread of the points giving a larger standard deviation of ± 33.9 W m^{-2} and r^2 = 0.9079; however, its performance can be considered as good in predicting the hourly latent heat flux (Figure 8). The present data set, which represents a much larger number of points analyzed (n = 1003), indicates that a slightly better fit would result if the intercept value of the above equation would be 32.6 instead of 20, giving an r^2 = 0.9319 and standard deviation of ±30.8 W m^{-2}.

Finally, if the actual value of S is incorporated into equation 2, then the best fit with a fixed value of α would be obtained with LE = 1.02 [s / (s + γ)] (Qn – G - S), which gave an r^2 = 0.9194 and standard deviation of ± 33.5 W m^{-2}.

Conclusions

The hourly energy balance of two forested areas of the Amazon region indicated that daytime change in canopy heat storage (S) is a significant term of the exuberant vegetation, being sometimes larger than the sensible heat flux, and as such it cannot be discarded from the budget. There was not a definite relationship between S and the above canopy net radiation (Qn) as suggested elsewhere; however, the assumption that it represents roughly 10% of Qn resulted in good performance of the Priestley-Taylor evapotranspiration model. Negative values of S enhances the above canopy latent heat flux and it is sometimes interpreted as contribution of local advection. The large mass of vegetation restricted the soil heat flux to a negligible value. Confirming previous work in forested areas, the latent heat consumed about 70% of the net radiation, and this is the simplest way to estimate forest evapotranspiration when soil water is not limited.

The Priestley-Taylor parameter was primarily determined by the sensible heat flux (H), as previously found for short vegetation, but also by the change in canopy heat storage (S). The fitted α function for the forest did not differ significantly from that determined for non-stressed grass field. However, α was negatively affected by S, with larger S values resulting in smaller α. The combined effect of S and H over α had the same tendency as that determined for H independently. This helps to explain why α is much smaller for forests than for short vegetation.

The above canopy latent heat flux given by the Priestley-Taylor model either with α estimated by the PEREIRA & VILLA NOVA (1992) function or by the VISWANADHAM et al. (1992) parameterization, both assuming that S = 0.1 Qn, did not differ significantly from the measured flux. This results substantiate both approaches. Even though the standard deviation was a little bit larger and the correlation coefficient somewhat smaller, the VISWANDHAM et al. (1992) parameterization should be preferred because it needs only Qn and above canopy air temperature as input variables.

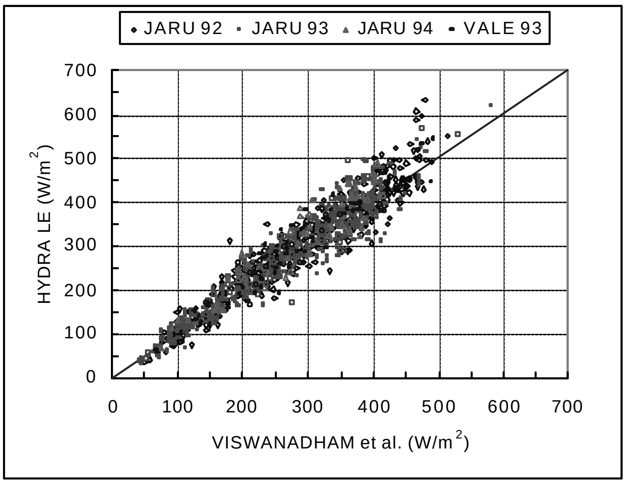

Figure 8. Relationship between measured and estimated LE, using the Priestley-Taylor model with α = 0.93 adapted by VISWANADHAM et al. (1992).

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