Revista Brasileira de Agrometeorologia, Santa Maria, v. 5, n. 2, p. i-viii, 1997.
Recebido para publicação em 24/09/97. Aprovado em 26/01/98.

RADIATION REGIME OF TROPICAL RAIN FOREST

REGIME RADIATIVO DE FLORESTAS TROPICAIS ÚMIDAS

Antonio Roberto Pereira[1]

Review / Revisão bibliográfica

SUMMARY

Because of their location along the equatorial region, tropical rain forests receives an amount of radiative energy (sun + sky radiation) which is approximately independent of the season and about 52 MJ m^{-2} d^{-1}. During overcast days, the reduced solar input is compensated by the increase in downward longwave radiation. On average, shortwave input amounts to 18 MJ m^{-2} d^{-1} (15 to 21 MJ m^{-2} d^{-1}) and the mean albedo (≈ 13 %) eliminates around 2.4 MJ m^{-2} d^{-1}; while the downward longwave inputs 34 MJ m^{-2} d^{-1}, the upward longwave dissipates 39 MJ m^{-2} d^{-1}, resulting in a net radiation (Rn) of 10.7 MJ m^{-2} d^{-1}. Mean monthly albedo shows a seasonal variation dictated mainly by the rainfall regime. Together, the energy used in photosynthesis, as heat stored in the phytomass and in the canopy air, and in the soil amount to 7 % of Rn. During the wet season, about 64 % of Rn is converted into latent heat (λE) and 29 % is used as sensible heat (H); but during the dry season the situation is reversed being 13 % of Rn converted into λE and 80 % into H. Consequently, the bowen ratio varies from 0.45 to over 6. Below the dense canopy, the dynamic nature of the sunflecks favors the growth and development of an understorey vegetation. Sampling schemes (point or ensemble) dictates the different figures reported in the literature, but in general, less than 10 % of the solar radiation reaches the forest floor and it amounts to 1.0 to 1.6 MJ m^{-2} d^{-1}. Sunflecks bursts can go up to 25 % of full sun and can last from 2 to 4 min. In some cases, such bursts can account for 30 % to 70 % of the total daily understorey of the photosynthetically active radiation (PAR). Therefore, the diffuse radiation dominates during most of the time. Also, the quality of the energy changes substantially because the vegetation uses most of the PAR, and at the forest floor the solar radiation contains, in general, only 25 % of PAR. Throughout the year, the PAR fraction which

[1] Associate Professor, Departamento de Física e Meteorologia, ESALQ/USP, 13418-900 Piracicaba, SP, Brazil. Fellow of the CNPq; e-mail: arpereir@carpa.ciagri.usp.br

reaches the forest floor is fairly constant and independent of the solar declination, and it amounts from 1 % to 3 % of the above canopy PAR.

Key words: albedo, net radiation, sunflecks, energy balance, bowen ratio, photosynthetically active radiation.

RESUMO

Em função de sua localização ao longo da região equatorial, florestas tropicais úmidas recebem uma quantidade de energia radiativa (radiação do sol + do céu) que é aproximadamente independente das estações do ano e que totalizam 52 MJ m^{-2} d^{-1}. Durante um dia nublado, a redução em energia solar é compensada pelo aumento da energia de ondas longas recebidas das nuvens. Em média, as ondas curtas representam 18 MJ m^{-2} d^{-1} (15 a 21 MJ m^{-2} d^{-1}) e o albedo médio (≈13 %) elimina 2,4 MJ m^{-2} d^{-1}; enquanto a entrada de ondas longas é de 34 MJ m^{-2} d^{-1}, a emissão pela superfície dissipa 39 MJ m^{-2} d^{-1}, resultando num saldo de radiação (Rn) de 10,7 MJ m^{-2} d^{-1}. O albedo médio mensal mostrou uma variação sazonal ditada principalmente pelo regime de chuvas. Juntos, a energia usada na fotossíntese, no aquecimento do ar da cobertura, no aquecimento da fitomassa, e no solo totaliza cerca de 7 % de Rn. Durante a estação chuvosa, cerca de 64 % de Rn é convertido em calor latente (λE) e 29 % em calor sensível (H); mas durante a estação seca a situação é revertida sendo 13 % de Rn convertido em λE e 80 % em H. Consequentemente, a razão de bowen varia entre 0,45 até mais de 6. Abaixo da cobertura, a natureza dinâmica das manchas de sol favorecem o crescimento e o desenvolvimento de uma vegetação de sub-bosque. O esquema de amostragem (ponto único ou multipontos) determinam os diferentes números relatados na literatura, mas em geral, menos de 10 % da radiação solar incidente atinge o piso da floresta, e ela totaliza de 1,0 a 1,6 MJ m^{-2} d^{-1}. Manchas de sol podem representar picos de até 25 % da radiação a pleno sol e durar de 2 a 4 min. Em alguns casos tais picos podem representar entre 30 % e 70 % do total diário da radiação fotossinteticamente ativa (RFA) no piso da floresta. Portanto, há domínio da radiação difusa na maior parte do tempo. A qualidade da energia também muda substancialmente porque a vegetação usa a maior parte da RFA, e em geral, no piso da floresta a radiação solar contém apenas 25 % de RFA. Durante todo o ano, a fração RFA que atinge o piso da floresta é praticamente constante e independente da declinação solar, e totaliza cerca de 1 % a 3 % da fração RFA acima da vegetação.

Palavras-chave: albedo, saldo de radiação, manchas de sol, balanço de energia, razão de bowen, radiação fotossintéticamente ativa.

INTRODUCTION

This article is a review of the radiation regime above and below the canopy, and of the partition among the major physical processes of conversion of such energy in tropical rain forest. Micrometeorology of tropical rain forest has gained special attention mainly because of the remarkable richness of life in these forests. Also, the vastitude of such ecosystems have always challenged the humankind. SHUTTLEWORTH (1989) compared temperate and tropical forests concluding that they have similar micrometeorological responses. However, over the Amazonia and the equatorial region, the major site of tropical rain forests, the daily solar energy input throughout the year is enormous and exploitation of such regions are likely to affect the global weather.

RADIATION REGIME ABOVE THE CANOPY

REFLECTION COEFFICIENT

Plant stand productivity is primarily determined by the ability of the plants in capturing and transforming solar radiation. The capture of solar radiation is a physical phenomenon determined, amongst many factors, by the size of the plants, by the way they exploit the available space, by the foliage color, size, orientation and spatial distribution, and by the angle of incidence of the sun's rays. One way to express the efficiency of radiation trapping is through the canopy reflection coefficient.

The incident solar radiation can be separated in two broad portions: one, called Photosynthetically Active Radiation (PAR), which includes the energy in the waveband between 400nm and 700nm; another, the Near Infrared Radiation (NIR), which is the energy of wavelengths greater than 700nm. The proportion of PAR and NIR in the incoming solar radiation at the earth surface is not constant, being a function of the amount of water vapor in the atmosphere, which filters out part of the NIR fraction, and the solar angle (b), which determines the depth of the atmosphere to be traversed by the sun rays. The PAR fraction can account from 46 % to over 70 % of the global radiation (McCREE, 1966; SZEICZ, 1974; STANHILL & FUCHS, 1977; STIGTER & MUSABILHA, 1982; WEISS & NORMAN, 1985). For a clear sky day the PAR fraction varied from about 40% around noon time to over 50% near sunrise and sunset, with an overall mean of 45%; while for an overcast day the variation was between 52% and 62% with mean of 56% (ASSUNÇÃO & BARBIERI, 1995). Plant canopies tend to maximize the absorption of PAR and the reflection of NIR (BILLINGS & MOORIS, 1951).

Reflection coefficient for vegetation is mainly a function of the solar angle and can be explained in terms of canopy leaf-angle architecture (LEMEUR & ROSENBERG, 1975). On short time scale (say, hourly), as the sun approaches the horizon, with the solar beam at grazing incidence, the reflection is almost specular regardless of the physical characteristics of the surface. However, as the sun angle increases, the myriad of leaf exposure imposes a scattering which decreases the upward reflection, thus increasing the radiation absorption by multiple reflections in the lower layers of the canopy. Consequently, the reflection coefficient is larger immediately after sunrise and before sunset with a daily minimum around noontime (10 a.m. to 2 p.m.) but, in this case, larger albedo are associated with low solar radiation input and vice-versa, and daily averages smooth such variations.

On longer time scales (say, monthly), seasonal changes in the structure of the forest also affects the albedo, and OGUNTOYINBO (1970) reported a seasonal variation of 7.5% in Nigeria. In Thailand, PINKER (1982) found the 10 am to 2 pm mean albedo to vary between 12.5%, during a dry month, and 10.3% during a wet month. Similarly, for an amazonian site (Reserva Ducke) ANDRÉ et al. (1988) have found the daily albedo to vary between 11-13%, during the wet season, and 12-14%, during the dry season. CULF et al. (1995, 1996) also reported a seasonal variation in the albedo for three amazonian forest sites, that is: 1) Reserva Ducke (2°57' S; 59°57' W; 80m), some 25 km northeast of Manaus, where the average tree height was 35m, with some trees reaching 40m; 2) Reserva Jaru (10°05'S; 61°55'W; 120 m), about 80 km north of Ji-Paraná, with mean canopy height of 33m; and 3) Reserva Vale do Rio Doce (5° 45'S; 49° 10'W), about 50 km south of Marabá, and mean canopy height of 20-25m. Reserva Ducke (RD) and Reserva Jaru (RJ) had almost identical and parallel variations with minimum values (RD, 10.9%; RJ, 12.1%) in April (wet month) and a maximum plateau from August to December (RD, 12.8%; RJ, 14%), the dry months. Reseva Ducke had always smaller albedo. For the Reserva Vale do Rio Doce (RV) there was a sharp increase in the albedo from March (12.7%) to April (14.2%), conditioned by an also sharp decrease in the rainfall, and the maximum plateau lasted from June to September (≈16.1%), the dry period. The annual mean albedo was equal to 12.1 ± 0.7% for RD, 13.3 ± 0.7% for RJ, and 14.9 ± 1.3% for RV. The annual amplitude was 1.3% at RD, 2.2% in RJ, and 3.8% at RV. It was also reported that the albedo was negatively related to the available soil moisture in the roots zone, that is, higher the soil moisture lower the albedo and vice-versa, explaining the seasonal variations.

For the Reserva Florestal Ducke, the above-canopy radiation balance has been measured on several occasions. At one time, SHUTTLEWORTH et al. (1984a) selected 94 hourly averages when the incoming solar radiation was greater than 20 W m^{-2} and the reflected radiation was greater than 1 W m^{-2}; therefore, near sunrise and sunset measurements were eliminated. The measurements were done during September when the solar declination is near zero and the solar angle varies most. Pooling the data in six groups, corresponding to the hours on either side of midday, they found that the reflection coefficient (ρs) could be described by a second degree polynomial with the solar angle (ß, in degrees) as the only variable, that is

$$\rho s = 15.09 - 0.136\, ß + 0.00123\, ß^{2}, \qquad (1)$$

with daily mean around 12.25 ± 0.2 %, and a small variation of ρs with ß.

With data collected at the same site (RD), also during September, but in a different experiment (1991) with different instruments, an almost identical relationship was found between ρs and b, which gave a daily mean value of 11.3 ± 0.8 % (LEITÃO, 1994). In other words, both sets of data for RD can be described by the same equation. For a forest site (6^{o} 33' N; 3^{o} 50' E) in Nigeria, with some trees reaching up to 40m, OGUNTOYINBO (1970) reported a mean daily (9 am to 3 pm) value of 13 ± 1 %. Diurnal variation was also reported for a Thailand forest at the Sakaerat experiment station (14° 31' N; 101° 55' E), in Khorat Plateau, where the canopy was composed by 20 - 32 m high trees, with an understorey of 5 - 17 m tall trees, and an additional undergrowth layer of 2.5 - 3.5 m (PINKER et al., 1980; PINKER, 1982). The Thailand forest albedo varied from about 11 %, around midday, to as high as 18-19 %, when the solar angle was between 10° and 20°, and was consistently larger than the amazonian (RD) which varied from about 10 % to 14-15 %, in the same solar angle range (SHUTTLEWORTH et al. 1984a; LEITÃO, 1994).

LEITÃO (1994) reported an asymmetry on the daily variation of the albedo, a fact that was not mentioned by SHUTTLEWORTH et al. (1984a). The afternoon values were consistently larger than the morning ones, and the same tendency was detected in two other amazonian ecosystems (campina and campinarana). Perhaps the smaller morning values were due to the presence of dew on the top of the canopies, and as they dried through evaporation the reflection increased slightly. OGUNTOYINBO (1970) reported unusually small values near sunrise and speculated that dew deposition on leaf surfaces was the cause. The normal tendency is for the afternoons to have higher temperature, vapor pressure deficits, and wind speed than the corresponding mornings. This combination increases the atmospheric demand for water vapor, thus the plants are more likely to be under water stress in the afternoon. The wind, which normally increases in the afternoon with thermal convection, sways branches and leaves changing the canopy architecture, may also have an effect on the albedo. Afternoon albedo higher than the forenoon equivalent was reported by IDSO et al. (1969) for short grass and bare soil, by PROCTOR et al. (1972) for an apple tree, and by NKEMDIRIM (1973) for several crops and bare ground. In the last two cases, this feature was attributed to a possible shift in the spectral composition of the incoming radiation due to haze and dust interference.

Diurnal asymmetry in the albedo of tropical evergreen forest had been previously reported by PINKER (1982), with data gathered at the Sakaerat forest reserve in Thailand. The asymmetry was pronounced during both clear and cloudy conditions; however, in this case the asymmetry was reversed with the morning albedo higher than the corresponding afternoon ones, regardless of sky conditions. Water stress was assumed to be responsible for this phenomenon, but the asymmetry was less pronounced during a day of a dry month. A nearby clearing site of approximately 500m in diameter, covered with low vegetation, mainly elephant grass, displayed the same asymmetry observed at the forest.

An alternative explanation for such results is a possible spectral shift with enrichment with PAR in the afternoon, a condition which depends on the increase in diffuse radiation (SZEICZ, 1974; STIGTER & MUSABILHA, 1982), normally due to the presence of clouds. However, during a completely overcast day, in the middle of the wet season, when the water stress cannot be invoked to explain the albedo asymmetry such feature was also displayed for both the forest and the grass site. Neither the spectral shift can be responsible for this occurrence for during an overcast day, when the radiation is totally diffuse, the PAR fraction dominates throughout the day.

Another intriguing result in Pinker's work is the larger albedo reported for the completely overcast day in comparison with the clear days. Pinker argues that this "could be a result of an enriched near infrared component of the global radiation during the cloudy conditions, and the high reflectance of this component by the vegetation". The second part of this statement is correct, but the first part is not since the presence of water vapor in the atmosphere increases the amount of visible radiation relative to infrared radiation (MONTEITH & UNSWORTH, 1990, p40). For very cloudy skies, in Dar es Salaam (7^{o} S), Tanzania, the PAR fraction accounted for over 60 % of the incoming solar radiation (STIGTER & MUSABILHA, 1982), and cloudiness tends to reduce the reflectivity (OGUNTOYINBO, 1970). From the many reports mentioned above, a smaller albedo is expected during a cloudy day and Pinker's results remain to be explained.

Albedo for the PAR and NIR fractions were also measured at the amazonian (RD) forest, and could well be described by the following statistical functions:

$$\rho NIR = 27.76 - 0.255\, ß + 0.00173\, ß^{2}, \qquad (2)$$

$$\rho PAR = 3.19 - 0.0262\, ß, \qquad (3)$$

showing that ρPAR is a weak linear function of ß (LEITÃO, 1994). The asymmetry discussed above for the overall shortwave albedo was also detected in ρPAR and ρNIR; however, it was much more pronounced for ρNIR, and almost imperceptible for ρPAR.

RADIATION BALANCE

PINKER et al. (1980) results indicate that the daily (24h) totals of the sun plus downward sky radiation were independent of the season. The daytime solar radiation showed a seasonal variation between 15 MJ m^{-2} d^{-1}, in August, and 21 MJ m-^{2} d-^{1}, in February, but the sky radiation compensated for the reduced solar radiation during the rainy season. On average, the forest received almost 52 MJ m^{-2} d^{-1}, with 17.6 MJ m^{-2} d^{-1} supplied by the sun (K↓) and 34.2 MJ m^{-2} d^{-1} by the sky (L↓). Solar input represented about 34 % of the incoming energy. Shortwave reflection (11.7 %) eliminated 2.1 MJ m^{-2} d^{-1} of the solar input, and longwave emission (L↑) dissipated 38.9 MJ m^{-2} d^{-1}, resulting in a daily net (Rn) input around 11 MJ m^{-2} d^{-1}. Similar figures were found for the Amazon forest by SHUTTLEWORTH et al. (1984a) and by CULF et al. (1996).

Data from ANDRÉ et al. (1988) show that Rn varied with the sunshine ratio (n/N) from 5.7 MJ m^{-2} d^{-1} (n/N = 0.2) to 16.5 MJ m^{-2} d^{-1} (n/N= 0.9). For a natural rain forest in Panama (Bayano river basin ~ 9º N), READ (1977) found Rn to vary in a similar range during the year, i.e., 3.5 MJ m^{-2} d^{-1}, in October (wet), to 17.7 MJ m^{-2} d^{-1}, in April (dry).

SHUTTLEWORTH et al. (1984a) had expressed some concern that the average solar input, for six days in an unusually wet September, represented only 40 % of the extra-terrestrial radiation (K↓ / Qo = 0.4), which they found to be significantly less than the 48 % figure assumed to be adequate for humid tropical regions. Data from ANDRÉ et al. (1988) show K↓/Qo between 0.36 and 0.70, depending on the sunshine ratio with peak values for K↓ varying from 400 W m^{-2}, when n/N = 0.2, to about 1000 W m^{-2}, when n/N = 0.9. Seasonal variation of K↓/Qo, with similar range, can also be inferred from PINKER et al. (1980), for the Thailand forest, and from CULF et al. (1996), for three amazonian sites. For the four sites the annual mean ratio and standard deviation were the following: a) Thailand forest: 0.496 ± 0.11; b) Reserva Ducke: 0.442 ± 0.048; c) Reserva Vale do Rio Doce: 0.486 ± 0.081; d) Reserva Jaru: 0.485 ± 0.058. The higher standard deviation for the Thailand forest is due to the smaller number of months (five) reported. As expected, K↓/Qo was determined by the monthly amount of rainfall, that is, higher ratios were obtained in drier months, and vice-versa. For Manaus, which is about 25 km southwest of the Reserva Ducke experimental site, data from RIBEIRO et al. (1982) indicate that K↓ /Qo = 0.26 + 0.49 n/N, which resulted in an annual average of K↓ / Qo = 0.43± 0.09. For two consecutive Septembers (1977/78), the monthly K↓ / Qo averages were 0.40 and 0.56, respectively. Consequently, Shuttleworth’s results are in the lower end of the range and were determined by the rainfall.

Daytime above the canopy net radiation has been found to be linearly correlated with the incoming solar radiation, or Rn = **a** + **b** K↓. Statistical analysis, with hourly or half-hourly data, indicate coefficient **b** to be fairly stable and in the interval 0.8 - 0.9, while coefficient **a** was always negative and variable (PINKER et al., 1980; SHUTTLEWORTH et al., 1984a; ANDRÉ et al., 1988; LEITÃO, 1994). Results from PINKER et al. (1980) seem to indicate an inverse relationship between **a** and the relative humidity (dew point temperature). Apparently, **a** increased asymptotically from -82 W m^{-2} to around -15 W m^{-2} as the relative humidity (RH) increased from 64 % to 82 %. There was a tendency for **a** to stabilize as RH reached 80 %. For the Amazonian forest, during a period of fairly constant and high specific humidity, **a** varied between -30 and -40 W m^{-2} (SHUTTLEWORTH et al., 1984a; ANDRÉ et al., 1988; LEITÃO, 1994).

Net 24h longwave radiation varied from -3.0 MJ/m^2.d, during an overcast day, to -7.0 MJ/m^2.d, on a relatively clear day. Nighttime longwave balance has been measured to be around -30 to -40 W m^{-2}, for the Amazon forest (SHUTTLEWORTH et al., 1984a; ANDRÉ et al., 1988), which correspond to the value found for the parameter **a** of the Rn vs K↓ relationship.

On a monthly time scale, data from CULF et al. (1996) show that the ratio Rn / K↓ is positively related to the specific humidity (q, g .kg^{-1}), that is, Rn / K↓ = 0.23 q + 0.028 (r^2 = 0.6815). In other words, higher the moisture in the air, greater the proportion of net radiation in relation to the incoming solar radiation.

RADIATION REGIME BELOW THE CANOPY

The characterization of the solar regime below a vegetated canopy is extremely difficult mainly due to the spatial distribution of the sunflecks, and by their dynamic nature throughout the day. Sampling such environment is not easy and it has been found that at least 12 sensors, distributed on 5m x 5m grid, were necessary to describe the average diurnal variation of the incoming solar radiation at the Reserva Ducke site (LEITÃO, 1994). However, ensemble average smoothes out fluctuations which are important from the ecological aspect.

Having in mind the sampling imperfections, it can be said that the floor of tropical rain forests receives, on average, less than 10 % of the solar radiation which reaches the canopy top (PINKER et al., 1980; SHUTTLEWORTH et al., 1984a; JANUÁRIO et al., 1992; LEITÃO, 1994). Throughout the year, PINKER et al. (1980) found that about 8 % of the solar energy was available to the understorey vegetation. In terms of energy, it amounted to 1.0 MJ m^{-2} d^{-1} in a wet month (August), and 1.6 MJ m^{-2} d^{-1} in February, a dry month. There was a 60 % variation in six months. Even though the solar input represented only 2 % to 5 % of the downward radiation, such fluctuations in shortwave energy has a tremendous impact on the growth of the understorey vegetation which lives in a less stressing environment.

For the Amazon forest, the transmission of solar radiation to the forest floor varied from 1.2 %, at the Reserva Ducke (SHUTTLEWORTH et al., 1984a), to 4.7 % in Tucurui, PA (JANUÁRIO et al., 1992). In the first case, the sensor was moved to new, randomly chosen, positions on alternate days, and after six consecutive days, in September, the overall solar radiation average was 4 W m^{-2} with hourly peaks barely reaching 10 W m^{-2}. In the second case, three sensors were randomly distributed beneath the canopy and 10-min averages were reported for each sensor, and peaks frequently reached 40 W m^{-2}, with one observation of 80 W m^{-2}; the daily transmission was computed by pooling the three sensors for a single day.

Leitão's results show also that the ensemble peak value depends on the number of sensors used. For instance, the peak reached 68 W m^{-2} with four sensors, 46 W m^{-2} with 8, 38 W m^{-2} with 12, and 35 W m^{-2} with 16. Obviously, the transmission percentage varies also with the sampling scheme, and in the present example it was equal to 7.6 %, 5.0 %, 4.2 %, and 3.9 %, respectively. It remains to be decided which figure gives the best description of such complex environment. Sometimes a point description is to be preferred because it brings out the occurrence of extremes; however, there are many studies where an area description is enough. The objective of the study dictates the sampling scheme and such problem has been addressed by REIFSNYDER et al. (1971).

Taking an ensemble average, the solar radiation which reaches the amazonian forest floor is composed by 25 % of PAR and 75 % of NIR, indicating the strong absorption of PAR by the foliage. Such proportion is similar to that found at the floor of an oak-hickory forest in Tennessee, USA, when fully-leafed (BALDOCCHI et al., 1984).

Long-term measurements of PAR at La Selva Biological Station, Costa Rica (10º 26' N; 32º 59' W), show that, throughout the year, the PAR fraction which reached the forest floor was fairly constant, independent of the solar declination, and between 1 % and 3 % of the above canopy PAR (RICH et al., 1993). Within a Sri Lankan tropical rainforest the total daily PAR on a sunny day was 1 % of full sun (ASHTON, 1992). In Manaus, about 1.3 % of the daily incoming PAR, 5.3 % of the NIR, and 3.2 % of the $K\downarrow$ reaches the forest floor (LEITÃO, 1994); applying the Beer - Bouguer law with a plant area index (PAI) of 5.4, determined by hemispherical photography, results in an extinction coefficient around 0.80 for PAR, 0.54 for NIR, and 0.63 for $K\downarrow$. These PAR and $K\downarrow$ extinction coefficients exceed those found for the fully-leafed Tennessee forest with equivalent PAI by as much as 35 %.

Sunflecks result from the penetration of sun rays through gaps in the canopy being a function of the solar angle and plant area index. Sunflecks bursts can reach up to 25 % of full sun and account for 30 to 70 % of total daily understorey PAR (ASHTON, 1992). For solar angle greater than 60º, sunfleck frequency increased substantially and lasted, on average, from 2 to 4 min (LEITÃO, 1994).

PARTITION OF THE AVAILABLE ENERGY

The available energy (Rn) which results from the radiation balance can be converted into latent (λE) and sensible heat (H), stored on the ground below the canopy (G) and on the canopy (S), and used on the photosynthesis (P). The photosynthetic process takes, on average, less than 3% of Rn, and for a mature forest such energy is used mostly for its own maintenance and for replacement of senescing tissues.

The energy stored in the soil during the day is normally released during the night, and on a 24-h basis it is frequently assumed to be zero; on a shorter time scale it can be different from zero, but rarely exceeded ± 6 W.m^{-2} at the Reserva Ducke site (MOORE & FISCH, 1986). Normally, G is a small fraction (about 1 %) of Rn (SANTOS et al., 1991).

The heat stored within the canopy both in the air and in the phytomass (S) has been found to be between 3 % and 5 % of Rn for the Amazon forest, but during overcast days with rainfall it can exceed 10 % of Rn (MOORE & FISCH, 1986). Heat storage in the canopy air (Sa) at the same site has been estimated to be less than 20 W m^{-2} (FITZJARRALD et al., 1988). An attempt to model the heat storage in the canopy air, Sa (W m^{-2}), as a linear function of the rate of change of air temperature ($\delta T/\delta t$, °C/h) and specific humidity ($\delta q/\delta t$, g/kg.h) at a level immediately above the canopy resulted in $Sa = 16.7\ \delta T/\delta t + 28\ \delta q/\delta t$, where **t** is time, while the heat stored in the phytomass was given by $Sb = 12.6\ \delta T^*/\delta t$, where the superscript * indicates that the temperature used was one hour in advance of the storage estimates (MOORE & FISCH, 1986). They indicate that the error associated with the combined estimates of S by such equations are about ±18 W m^{-2}; it was also noted that the estimates of Sb should be limited to about ±30 W m^{-2} when large changes in air temperature occur. Close to sunrise and sunset S can be larger than Rn (SANTOS et al., 1991). It is clear that S can be a very significant term in the energy balance of tall, dense vegetation such as the tropical rain forest and should not be taken as negligible.

However, most of the available energy is shared by λE and H on a complementary basis. If plenty of water is available to the forest, then most of Rn is converted into λE, giving a small Bowen ratio ($B = H/\lambda E$). Conversely, if there is a shortage of water, then a larger fraction of Rn goes into H, thus heating the atmosphere and resulting in a larger B. Results of PINKER et al. (1980) show that during a wet month (June, 122 mm of rain), λE used an equivalent of 8.2 MJ m^{-2} d^{-1} and H amounted to 3.7 MJ m^{-2} d^{-1}

resulting in B = 0.45; but during a dry month (January, 11mm of rain), only 1.5 MJ m^{-2} d^{-1} was used as λE but H reached about 10 MJ m^{-2} d^{-1} or B = 6.7. On a daily time scale, λE accounted for 70% to 80 % of Rn (SHUTTLEWORTH et al., 1984b; VISWANADHAM et al., 1990); on an hourly basis it varied from 59 % to 90 % (VISWANADHAM et al., 1990, 1991). Midday average values of λE was about 300 W m^{-2}, but extreme values reaching between 500 and 700 W m^{-2} is not uncommon (SHUTTLEWORTH et al., 1984b; FITZJARRALD et al., 1988; VISWANADHAM et al., 1990, 1992). Late afternoon λE values greater than Rn can be observed and such occurrence has been attributed to the non-homogeneous patchy nature of the forest which can cause advection of hotter and/or drier air (VISWANADHAM et al., 1990).

Daily totals of λE averaged 8.31±1.97 MJ m^{-2} d^{-1} for the Amazon forest (SHUTTLEWORTH et al., 1984b; VISWANADHAM et al., 1990). During an overcast day (n/N = 0.2) λE was equal to 3.5 MJ m^{-2} d^{-1}, while on a clear day (n/N = 0.9) λE reached 13 MJ m^{-2} d^{-1} (ANDRÉ et al., 1988). Potential evapotranspiration estimation for the Manaus site varied from 8.8 MJ m^{-2} d^{-1}, in April, to 12.7 MJ m^{-2} d^{-1}, in September (VILLA NOVA et al., 1976).

Results of independent measurements of Rn, λE and H show that, on a daily time basis, the summation S + G + P represented 0.59 ± 0.92 MJ m^{-2} d^{-1}, or 7 % of Rn (SHUTTLEWORTH et al., 1984b; VISWANADHAM et al., 1990). Consequently, such amount of energy cannot be assumed to be negligible, otherwise it will be incorporated, during the computations, either on λE or on H, thus increasing the degree of uncertainty of such terms.

CONCLUDING REMARKS

Eventhough tropical rain forest are evergreen, there was a seasonal variation in the monthly albedo imposed by the rhythm of the rainfall regime. However, it is not clear if such variation was due to: i) changes in the canopy structure imposed by water stress; ii) the presence/absence of free water (dew or rain) on the leaves; iii) a spectral shift in the incident radiation due to changes in the atmospheric composition; or, iv) a combination of all three factors. On an hourly time scale, in some cases, there was an asymmetry in the albedo with afternoon values consistently larger than the morning ones, but in one case this situation was reversed regardless of the sky conditions, and a combination of all three factors mentioned above can be invoked to explain such behavior.

It is interesting to note that the daily (24h) totals of solar plus downward sky radiation were fairly constant and independent of the season, that is, the sky radiation compensated for the reduction in the solar radiation input. Solar radiation accounted for 30% to 40% of the incoming energy being the remainder (60% to 70%) supplied by the sky. On average, longwave emission by the canopy dissipated

75% of the incoming radiation. As expected, the daytime net radiation and the incoming solar radiation had a linear relationship with fairly stable angular coefficient but with variable y-intercept, which was always negative and an asymptotical function of the ambient relative humidity (dew point temperature). Consequently, the ratio between net and incoming solar radiation was a positive linear function of the specific humidity.

Below the canopy the characterization of the radiation regime is strongly dependent on the sampling scheme (point versus area description) and the number of sensors used. However, it can inferred that the forest floor received less than 10% of full sun, but sunflecks bursts can reach up to 25% of the incoming solar energy and can last from 2 to 4 min. The selective absorption characteristics of the leaves imposes an spectral shift in the solar radiation at the forest floor which was found to be composed, on average, of 25% of PAR and 75% of NIR. In some cases, sunflecks bursts can account for 30% to 70% of the daily total understorey PAR because diffuse radiation dominates during most of the time.

During the rainy season most of the available energy was used as latent heat giving a small bowen ratio (≈0.5), but during dry spells latent heat conversion was restricted and most of the energy went into sensible heat giving bowen ratio larger than 6. Heat stored in the canopy air and in the phytomass can go up to 10% of the net radiation and this is a substantial amount of energy that cannot be neglected in energy balance. Latent heat in excess of the net radiation can be observed in the late afternoon and was attributed to the patchy nature of the forest inducing a local advection.

REFERENCES

ANDRÉ, R.G.B., SILVA FILHO, V.P., MOLION, L.C.B et al. Balanço de radiação solar sobre a floresta amazônica (estações sêca e úmida). **Rev Bras Meteorol,** v. 3, p. 269-274, 1988.

ASHTON, P.M.S. Some measurements of the microclimate within a Sri Lankan tropical rainforest. **Agric For Meteorol, v.** 59, p. 217-235, 1992.

ASSUNÇÃO, H.F., BARBIERI, V. Estimativa da radiação fotossinteticamente ativa e a sua distribuição espectral horária para Piracicaba - SP. In: CONGRESSO BRASILEIRO DE AGROMETEOROLOGIA, 1995. Campina Grande - PB. **Anais**..., Sociedade Brasileira de Agrometeorologia, 1995, p. 286-289.

BALDOCCHI, D.B., HUTCHISON, B.A., MATT, D.R. et al. Solar radiation within an oak-hickory forest: an evaluation of the extinction coefficients for several radiation components during fully-leafed and leafless periods. **Agric For Meteorol,** v. 32, p. 307-322, 1984.

BILLINGS, W.D., MORRIS, R.J. Reflection of visible and infrared radiation from leaves of different ecological groups. **Amer J Bot,** v. 38, p. 327-331, 1951.

CULF, A.D., FISCH, G, HODNETT, M.G.. The albedo of Amazonian forest and ranchland. **J Climate**, v. 8, p. 1544-1554, 1995.

CULF, A.D., ESTEVES, J.L., MARQUES FILHO, A.O. et al. Radiation, temperature and humidity over forest and pasture in Amazonia. P. 175-191. In GASH, J.H.C., NOBRE, C.A., ROBERTS, J.M. et al. (Editors), **Amazonia Deforestation and Climate**, John Wiley & Sons, 1966, 611 p.

FISCH, G **Armazenamento e fluxos de energia sobre floresta da Amazônia Central**. São Paulo, 99 p. Dissertação (mestrado), Universidade de São Paulo, Brazil. 1986.

FITZJARRALD, D.R., STORMWIND, B.L., FISCH, G. et al. Turbulent transport observed just above the Amazon forest. **J of Geophys Res,** v. 93, p. 1551-1563, 1988.

IDSO, S.B., BAKER, D.G., BLAD, B.L.. Relations of radiation fluxes over natural surfaces. **Quart J R Met Soc**, v. 95, p. 244-257, 1969.

JANUÁRIO, M., VISWANADHAM, Y., SENNA, R.C. Radiação solar total dentro e fora da floresta tropical úmida de terra firme (Tucuruí, Pará). **Acta Amazônica,** v. 22, p. 335-340, 1992.

LEITÃO, MMVBR **Balanço de radiação em três ecossistemas da floresta amazônica: campina, campinarana e mata densa**. São José dos Campos, 1994, 135 p. Tese (Doutorado em Meteorologia) – Instituto Nacional de Pesquisas Espaciais, 1994.

LEMEUR, R., ROSENBERG, N.J. Reflectant induced modification of soybean canopy radiation balance. II - A quantitative and qualitative analysis of radiation reflected from a green soybean canopy. **Agron J,** v. 67, p. 301-306, 1975.

McCREE, K.J. A solarimeter for measuring photosynthetically active radiation. **Agric Meteorol,** v. 3, p. 353-363, 1966.

MONTEITH, J.L., UNSWORTH M.H. **Principles of environmental physics**. Edward Arnold, 2nd ed., London. 1990, 291 p.

MOORE, C.J., FISCH, G. Estimating heat storage in Amazonian tropical forest. **Agric For Meteorol,** v. 38, p. 147-169, 1986.

NKEMDIRIM, L.C. Radiative flux relations over crops. **Agric Meteorol,** v. 11, p. 229-242, 1973.

OGUNTOYINBO, J.S. Reflection coefficient of natural vegetation, crops and urban surfaces in Nigeria. **Quart J R Met Soc,** v. 96, p. 430-441, 1970.

PINKER, R.T. The diurnal asymmetry in the albedo of tropical forest vegetation. **Forest Sci,** v. 28, p. 297-304, 1982.

PINKER, R.T., THOMPSON, O.E., ECK, T.F. The albedo of a tropical evergreen forest. **Quart J R Met Soc,** v. 106, p. 551-558, 1980.

PROCTOR, J.T.A., KYLE, W.J, DAVIES, J.A. The radiation balance of an apple tree. **Can J Bot,** v. 50, p. 1731-1740, 1972.

READ, R.G. Microclimate as background environment for ecological studies of insects in a tropical forest**. J Appl Meteorol,** v. 16, p. 1282-1291, 1977.

REIFSNYDER, W.E., FURNIVAL, G.M., HOROWITZ, J.L. Spatial and temporal distribution of solar radiation beneath forest canopies. **Agric Meterol,** v. 9, p. 21-37, 1971.

RIBEIRO, M.N.G., SALATI E., VILLA NOVA, N.A. et al. Radiação solar disponível em Manaus (AM) e sua relação com a duração do brilho solar. **Acta Amazônica,** v. 12, p. 339-346, 1982.

RICH, P.M., CLARK, D.B., CLARK, D.A. et al. Long-term study of solar radiation regimes in a tropical wet forest using quantum sensors and hemispherical photography. **Agric For Meteorol,** v. 65, p. 107-127, 1993.

SANTOS, R.C.; VISWANADHAM, Y., SANTOS, J.M. **Energy balance storage term in the Amazon forest**. 20th Conference on Agricultural and Forest Meteorology, Amer Met Soc, Boston. 1991, p 203-206.

SHUTTLEWORTH, W.J. Micrometeorology of temperate and tropical forest. **Phil Trans R Soc Lond B**, v. 324,p. 299- 334, 1989.

SHUTTLEWORTH, W.J., GASH, J.H.C., LLOYD, C.R. et al. Observations of radiation exchange above and below Amazonian forest. **Quart J R Met Soc,** v. 110, p. 1163-1169, 1984a.

SHUTTLEWORTH, W.J.; GASH, J.H.C.; LLOYD, C.R. et al. Eddy correlation measurements of energy partition for Amazonian forest. **Quart J R Met Soc,** v. 110, p. 1143-1168, 1984b.

STANHILL, G., FUCHS, M. The relative flux density of photosynthetically active radiation. **J Appl Ecol,** v. 14, p. 317-322, 1977.

STIGTER, C.J., MUSABILHA, V.M.M. The conservative ratio of photosynthetically active to total radiation in the tropics. **J Appl Ecol,** v. 19, p. 853-858, 1982.

SZEICZ, G. Solar radiation for plant growth. **J Appl Ecol,** v. 11, p. 617-636, 1974.

VILLA NOVA, N.A., SALATI, E., MATSUI, E. Estimativa da evapotranspiração na Bacia Amazônica. **Acta Amazônica,** v. 6, p. 215-228, 1976.

VISWANADHAM, Y., MOLION, L.C.B., MANZI, A.O. et al. Micrometeorological measurements in Amazon forest during GTE/ABLE 2A Mission.. **J Geophys Res,** v. 95, p. 13669-13682, 1990.

VISWANADHAM, Y., SANTOS, R.C., SANTOS, J.M**. The Amazon boundary layer experiment and its impact on regional climate**. 5th Conference on Climate Variations, Amer Met Soc, Boston, p. 274-277, 1991.

VISWANADHAM, Y., SANTOS, R.C., GIELOW, R Evaluation of an empirical expression to estimate evaporation over the Amazon forest. In: Schwartz S.E., Slinn W.G.N. (ed) **Precipitation scavenging and atmosphere - surface exchange**, v. 2. Hemisphere Publ. Co., Washington, p. 763-770, 1992.

WEISS, A., NORMAN, J.N. Partitioning solar radiation into direct and diffuse, visible and near-infrared components. **Agric For Meteorol,** v. 34, p. 205-213, 1985.