1. Publication Nº	2. Version	3. Date	5. Distribution
INPE-3515-PRE/740		May, 1985	☐ Internal ☒ External ☐ Restricted

4. Origin	Program
DME	TECLIM/MICRA

6. Key words - selected by the author(s)
MICROMETEOROLOGY
FOREST
AMAZON

7. U.D.C.: 551.584.41(811.3)

8. Title INPE-3515-PRE/740

THE MICROMETEOROLOGY OF AN AMAZONIAN RAINFOREST

10. Nº of pages: 35

11. Last page: 32

12. Revised by

Robert E. Dickinson

9. Authorship Luiz Carlos Baldicero Molion

Responsible author

13. Authorized by

Marco Antonio Raupp
Director General

14. Abstract/Notes

This paper reports the results of the first field campaign of Anglo-Brazilian collaborative study of the micrometeorology of the Amazonian rainforest, which was carried out on a site 25 km NE of Manaus, Brazil during September 1983. These preliminary results indicate that the albedo of the rainforest is about 12 percent and 75 percent of the available energy is used for evapotranspiration on dry days, with a Bowen ratio of about 0.3. It was observed that 17 percent of rainfall, during the study period, was intercepted by the canopy and the calculations indicate that 48 percent of the rainfall returned to the atmosphere through evapotranspiration. Wind profile parameters are in close agreement with results reported for temperate forests. The daily cycles of temperature, humidity and humidity deficit are also discussed.

15. Remarks To be published as Chapter 8 of "Geophysiology of Amazonia" RE. Dickinson, ed. John Wiley & Sons Inc.

8. THE MICROMETEOROLOGY OF AN AMAZONIAN RAINFOREST

Luiz Carlos Baldicero Molion

Instituto de Pesquisas Espaciais
Conselho Nacional de Desenvolvimento
Científico e Tecnológico
C.P. 515
12200 São José dos Campos - São Paulo
Brasil

ABSTRACT

This paper reports the results of the first field campaign of Anglo-Brazilian collaborative study of the micrometeorology of the Amazonian rainforest, which was carried out on a site 25 km NE of Manaus, Brazil during September 1983. These preliminary results indicate that the albedo of the rainforest is about 12 percent and 75 percent of the available energy is used for evapotranspiration on dry days, with a Bowen ratio of about 0.3. It was observed that 17 percent of rainfall, during the study period, was intercepted by the canopy and the calculations indicate that 48 percent of the rainfall returned to the atmosphere through evapotranspiration. Wind profile parameters are in close agreement with results reported for temperate forests. The daily cycles of temperature, humidity and humidity deficit are also discussed.

8.1 - INTRODUCTION

The major part of the energy available for physical processes occurring in the troposphere, particularly for the general circulation of the atmosphere which causes the weather and climate, is provided by the Earth's surface through its interaction with incident solar radiation. This energy enters the atmosphere mainly in the form of vertical fluxes of latent and sensible heat through the boundary layer. Except for a narrow strip near the equator over the oceans -- the intertropical convergence zone - where latent heat is also released, the main sources of heat are the equatorial portions of the continents which are mostly covered with natural forests. Although the role of tropical forests as heat sources for the general circulation is widely recognized, few experimental studies have tried to quantify this exchange of energy between the forest and the atmosphere. The works of Jackson (1971) in Tanzania, Read (1977) in the Panama Canal Zone and Heuveldop (1979) in Venezuela can be cited as examples.

This work describes results from the first field campaign of a major Anglo-Brazilian collaborative study of the micrometeorology and plant physiology of the Amazonian rainforest, most of which appear in Shuttleworth et al. (1984 a, b and c). The measurements were made using a 45m scaffolding tower located at a site selected as representative of the natural vegetation and regional topography in the Ducke Reserve (INPA/CNPq), 25km NE of Manaus, at lat. $2^{o}57'$S, long. $59^{o}57'$W. Plant density is high, up to 3000 stem ha^{-1}, but less than 10 percent have girths of 0.2m or more. The forest canopy around the tower extends to a height of about 35m with occasional emergent trees reaching over 40m. There are no obvious substories. The middle and lower parts of the canopy are made up of more but individually smaller plants. Ground level vegetation is scarce, and rooting in the yellow laterite soil is shallow, with a dense root mat down to 0.15m and a few tap roots deep in the soil.

Micrometeorological measurements are described in the following sections. Besides phytophysiological data, which will be reported elsewhere, there are parallel measurements of rainfall interception made in a attempt to determine the partitioning of the evaporation into transpiration and interception loss. The direct soil evaporation does not appear to contribute significantly. Measurements of rainfall amount reaching the ground were made with 16 raingauges which were relocated randomly along a linear transect after each storm.

8.2 - RADIATION EXCHANGE

The radiation balance for the "active canopy" surface is written as:

$$R_n = S\downarrow - S\uparrow - L\uparrow + L\downarrow - RL\downarrow \quad (1)$$

where

- R_n is the radiation balance or net radiation;
- $S\downarrow$ is the incoming solar radiation;
- $S\uparrow$ is the reflected solar radiation;
- $L\uparrow$ is the longwave radiation emitted by the surface;
- $L\downarrow$ is the downward longwave radiation;
- $RL\downarrow$ is the reflected downward longwave radiation.

All quantities are in flux units.
Using the definitions of surface albedo (a), surface emissivity (ε) and the Stefan-Boltzmann Law, Equation (1) is rewritten as:

$$R_n = S\downarrow(1-a) - \varepsilon\sigma T_s^4 + L\downarrow - (1-\varepsilon)L\downarrow \quad (2)$$

Where T_s is the surface temperature. The emissivity (ε) for natural vegetation lies usually between 0.95 and 0.98 and for practical purposes it can be considered as a black body (ε=1) so that the last term in Equation (2) may be neglected.

All terms in Equation (1) can be measured except for $L\uparrow$ which has to be estimated. With the aid of a unidirectional radiometer it is possible to measure all-wavelength downward radiation ($U=S\downarrow + L\downarrow$). In this instrument, the lower plastic dome on a standard Funk type temperature of which is measured with a calibrated thermistor. So $L\uparrow$ and $L\downarrow$ can be derived from combinations of the measured fluxes.

The upward component of longwave radiation can also be calculated assuming that the mean surface temperature and mean measured air temperature at canopy level are equal and the surface emissivity equals one. It should be remembered, however, that the long wave components are particularly sensitive to error since they are calculated as a combination of several measured fluxes. A net radiation measurement at a single location may have an error of about ± 5% (Federer, 1968; McNeil and Shuttleworth, 1975).

Figure 1 from Shuttleworth et al (1984a) presents the average diurnal variation of short and longwave components of the radiation flux and the net radiation for 6 days of continuous data above the Amazonian rain forest near Manaus. On the average, solar radiation peaks before midday and then falls slightly in the afternoon, presumably in response to increasing cloudiness. Hourly average solar radiation exceeded 900 Wm^{-2} on rare occasions but peak daily values of 500 to 700 Wm^{-2} were more commom. During the day, the net radiation followed the behaviour of solar radiation very closely, with average maximum around 500 Wm^{-2}, and through the nighttime was rather constant around a value of -40 Wm^{-2}. The upward and downward longwave radiation fluxes have a small diurnal variation, with the net longwave radiation loss slightly increased around midday because of higher canopy temperature. The mean upward flux was approximately 452 Wm^{-2} and the mean downward flux equal to

412 Wm^{-2}. The Angström ratio, i. e., the fractional net loss was about 9 per cent.

Figure 2, extracted from the same work, shows the above and below-canopy fluxes of solar and net radiation in the form of hourly mean and standard error for the same period. The below-canopy solar radiation peaks before midday, probably because of sunlight penetration at low solar angles. The same may not happen in the afternoon because of cloudiness.

On the average the solar radiation reaching the ground was 1.2 per cent of that above the canopy, that is, an average flux of about 4 Wm^{-2}. The below-canopy net radiation lags behind the above canopy net radiation by about an hour and provides an average positive input of about 0.06 MJm^{-2} over 24 hours, approximately equal to the input of below-canopy solar radiation. The observed morning peak may be related to the structure of the main canopy allowing sunlight penetration at low solar angles; the afternoon peak, may be a result not only of to light penetration but also of main canopy heating since maximum temperature is observed near this time of the day.

The percentage variability in the below-canopy fluxes is significantly greater than that in the above-canopy fluxes, as the error bars in Figure 2 indicate. These fluxes are subject to sampling errors in addition to the fact the data may represent a less than perfect spatial average.

The major factors which regulate the albedo of tall vegetation are solar zenith angle, cloudiness, wetness and spectral properties of vegetation. The density, height and geometric configuration would also be expected to be of significance. In the case of an ideal rough surface, the albedo should be independent of the direction of the radiation beam. Pinker et al. (1980) analysed a large amount of solar radiation data to determine the mean albedo of a tropical evergreen forest in Thailand. They found a mean albedo of 13% with a strong diurnal variation during clear days ranging from about 11% around midday to as high as 18-19% in early morning or late afternoon. The variation is largely suppressed on overcast days, when the midday albedo was higher than on the clear days.

Shuttleworth et al. (1984a) reported a mean albedo value of about 12% for the Amazon rain forest and less diurnal variation. In overcast conditions the albedo behaviour was consistent with results of Pinker et al. (1980). For a tropical forest in Nigeria, Oguntoyinbo (1970) reported a values of 13%.

As pointed out in Shuttleworth et al. (1984a), changes in measured reflection ratio are very sensitive to experimental errors at low solar altitudes. Fortunately, a common practice is the use of the mean albedo, calculated from integrated daily fluxes of incoming and reflected solar radiation for daily energy budget calculations, which avoids dealing with the solar altitude dependence.

8.3 - ENERGY EXCHANGE

The energy balance of the forest, neglecting the energy used in photochemical reactions and assuming horizontal homogeneity, i. e. no energy advection, can be written as:

$$A = \lambda E + H = R_n - G - S \qquad (3)$$

Where:

A is the available energy;

λE is the latent heat into the air;

H is the sensible heat into the air;

R_n is the net radiation;

G is the energy going into the ground;

S is the energy going into storage.

All the quantities are in flux units.

As stated before, the net radiation flux can be measured with an error of ± 5% or less with net-radiometers mounted at the end of long booms. The heat flux into the Amazon forest soil is small; Shuttleworth et al. (1984a) reported an hourly average on the order of 4 Wm^{-2} entering the soil during the day and leaving it during the night.

This value is typically 1% of the net radiation for dense forest vegetation. The energy going into storage is obtained from measurements of the change in canopy temperature and humidity with time and from the canopy heat capacity (see, e. g. Stewart and Thom, 1973; McNeil and Shutlleworth, 1975). Spittlehouse and Black (1980) discussed the dificulty in estimating G and S for forests. Nevertheless they claim that, except for periods around sunrise and sunset, (G + S) is < 5% of the net radiation flux so that even a 50% error in this sum would result in a minor error in the available energy measurement.

For a tropical forest, however, the presence of a storage term in the energy budget may add considerable complexity to the computation of the available energy and its partioning. Simple modeling of this component proved incapable of describing sustained nightime radiation (Thompson, 1979); recent sophisticated computer models(e. g., Goudriaan, 1979) suggest that storage can be a significant contribution to the energy budget, both in terms of magnitude and of duration. The size, complexity and density of tropical forest is such that energy storage is likely to be a particularly important component, but difficult to calculate.

One possible way of avoiding the calculation of S is to assume that the cumulative sum of daily S values over a period of several days is approximately zero. Equation (3) then is rewritten as:

$$\sum A = \sum (\lambda E + H) = \sum R_n \qquad (4)$$

It should be remembered that this equality is not completely definitive in that it cannot rule out the possibility of a fortuitous numerical cancellation between daytime and nighttime errors.

Under this assumption, the problem is now reduced to partitioning of the available energy between latent and sensible heating. Spittlehouse and Black (1980) have given an excellent review of such methods.

Two methods were applied to the Amazon Tropical forest. The eddy correlation and the Bowen Ratio methods. The eddy correlation technique used a measuring system named Hydra which consists of a vertical sonic anemometer (Shuttleworth et al.;1982), a single beam infrared hygrometer (Moore, 1983), a 50μm thermocouple thermometer and two Gill propeller anemometers mounted orthogonally to measure the horizontal wind. With this technique it is possible to measure the latent heat flux (λE) and the sensible heat flux (H) directly. For eight complete days the comparison of cumulative net radiation and the cumulative sum of ($\lambda E + H$) was satisfactory, at about a five percent level; the integration over all eight days indicated a flux loss in the eddy correlation measurements of 6.3 MJm^{-2} for a total radiant input of 96.5 MJm^{-2}. The "evaporative fraction", defined in two ways as

$$\alpha = \sum\lambda E/\sum(\lambda E + H) \qquad (5a)$$

and

$$\alpha' = \sum\lambda E/\sum R_n \qquad (5b)$$

for the eight fine days gave and average daily value of 0.723±0.061 with α values generally higher than α' because of the integrated eddy flux loss mentioned above. Figure 3 extracted from Shuttleworth et al. (1984b) illustrates the energy partition for the eight days considered in their analyses.

The Bowen ratio (β) is defined as the ratio of sensible heat flux to the latent heat flux ($\beta = H/\lambda E$). If it is assumed that the fluxes obey a diffusion law and that the eddy diffusivities for heat and water vapour are equal, then near neutral conditions the Bowen ratio reduces to

$$\beta = \frac{c_p}{\lambda} \frac{\Delta\Theta}{\Delta q} \qquad (6)$$

Where:

Θ is the potential temperature;

q is the specific humidity;

c_p is the specific heat of air at constant pressure;

λ is the latent heat of vaporisation of water.

The evaporative ratio is readily calculated from this ratio through the expression $\alpha = (1+\beta)^{-1}$. The differential measurements of temperature and humidity were made using a reversing psychrometers system (TIS) described by McNeil and Shuttleworth (1975). Vertical gradients over a rough forest surface tend to be small and therefore difficult to measure accurately. By reversing the psychrometers systematic errors can be made to cancel in order to obtain a more accurate gradient. The daily α values resulting from TIS measurements are in general agreement with the ones calculated through the eddy correlation method, with the TIS results tending to show slightly lower values of evaporative ratio. On dry days, the average evaporative fraction of about 0.75 corresponds to a Bowen ratio of about 0.3. The data collected over the Amazonian forest implies that on the average about 75% of the available energy goes into evaporating water and the remaining 25% is used to heat the air. For a daily average of 4.96 mm water equivalent of radiation, 3.70 mm were evaporated into the air.

The evaporation flux from tropical forests consists of both transpiration by plants and rainfall which is intercepted by the canopy. Tropical forest interception range from as low as 13% of incident rainfall(Jordan and Heuveldop, 1981) for the Amazon forest at San Carlos de Rio Negro to as high as 50% (Read, 1977) for the Panama Canal forest.

Shuttleworth et al. (1984b) reported a preliminary value of 17% interception loss measured during 25 days in September 1983 at a site near the tower. Franken et al. (1982), at a different site 40km from Manaus but with similar environment found an average value of 22% for a one-year period. Shuttleworth et al. (1984b) also estimated that, during the period of measurements, 48% of the precipitation falling on the site returned to the atmosphere by evapotranspiration.

o This value for total evapotranspiration is in close agreement with the results published by Jordan and Heuveldop (1981). If the interception loss is 17% and direct soil evaporation can be disregarded,then transpiration is responsible for 31% of the rainfall loss.

8.4 - VERTICAL STRUCTURE OF WIND, TEMPERATURE AND HUMIDITY

The profile of the mean horizontal wind in the atmospheric surface layer over natural surfaces is generally logarithmic in neutral stability conditions (see e. g., Tenekes and Lumley, 1972). Above tall vegetation

$$u\ (z) = \frac{u^*}{k} \ln \left\{ \frac{z - d}{z_o} \right\} \tag{7}$$

where u (z) is the mean horizontal wind at a height z above the ground, u* is the friction velocity, k is the von

Karman's constant, z_o is the roughness lenght and d is the zero-plane displacement. The values of d were computed using the mass conservation method (Molion and Moore, 1983), which are used in conjunction with the least squares method to determine u* and z_o.

The Amazonian forest site used presents no problem of fetch, with height to fetch ratios smaller than 1/700. For the data set collected in September 1983, only 24 profiles were found to be in near neutral conditions ($0.008 \leq - dT/dZ \leq 0.012^oC\ m^{-1}$). Speeds were above 2.00m s^{-1} at the highest measurements level which was about 10 m above the mean canopy. The estimated values for d = 25.30 ± 0.62 m and z_o = 4.96 ± 0.38 m, correspond to 0.72 ± 0.02 h and 0.14 ± 0.01 h, respectively, where h is the mean canopy height equal to about 35 m.

The values of u* = 0.79 ± 0.13 m s^{-1} calculated from Equation (7) seem to be high considering that in this set of profiles the uppermost level wind did not exceed 4.00 m s^{-1}. The u* values measured with the "Hydra" had an average which is about half of the u* calculated from Equation (7).

The zero-plane displacement and aerodynamic roughness, however, seem to be in good agreement with values reported for temperate forests. At this stage, it is difficult to draw conclusions about these parameters and it is expected that coming field campaigns will elucidate the question.

Below the canopy the mean horizontal wind speeds were usually between 0.00 and 1.00 m s^{-1}. In this range the cup anemometers used are not accurate so the wind profile below the canopy was not estimated.

The temperature and humidity data were collected using psychrometers described by Gash and Stewart (1975). Figure 4 illustrates how they were arranged with the double reversing psychrometers system (TIS), described by McNeil and Shuttleworth (1975), located above the canopy surface. Although wet and dry bulb thermometers were well calibrated, it would be unrealistic to assume that the measurements represent the spatial average at each level to accuracies better than, say, 0.1^{o}C in temperature and 0.2 g kg^{-1} in humidity.

Figure 5 from Shuttleworth et al. (1984c) presents data of temperature and humidity for two consecutive days which are of particular interest because they provide a comparison between a dry day and a day when two short rainstorms occurred. This figure suggests that mixing in the top two thirds of the canopy is quite efficient during daylight hours with temperature, humidity and humidity deficit following those of the air above to within about 1^{o}C and 2 g Kg^{-1}, respectively, in dry conditions. On the other hand, the bottom third seems to undergo a less pronounced daily cycle with the amplitude of temperature being about 60% of that at the canopy top, specific humidity higher by about 2 g kg^{-1} and humidity deficit only 30 to 50 percent of above canopy values. At night the behaviour is reversed with temperature of the air in the upper part of the canopy significantly decoupled from that in the lower two thirds. Possibly the air at the canopy top cools by radiative losses and sinks down, replacing the warmer air which is forced to rise. The nighttime radiation losses may be sustained by this energy from the warmer air which is stored below the canopy during the day. In dry nighttime conditions there is a small variation in temperature and specific humidity deficit through the bottom two thirds of the canopy. Above this level, they have significantly higher values. The specific humidity varies but little throughout the canopy. When rain started at 6:00 and 15:00LT both temperature and specific humidity fell sharply at all levels, perhaps due to cool downdraughts and cooling by evaporation. The humidity deficit at the top level was significantly reduced, say by about 3 g kg^{-1}, when compared to the previous day. However, a few hours later the humidity deficit at the upper two thirds exhibited remarkably little differences compared to the previous day as if the canopy were already dry. The bottom level showed a noticeable reduction in the humidity deficit throughout the wet day.

Figure 6 shows the differences in temperature and specific humidity above the canopy as measured with TIS. The broken line indicates the behaviour on the dry day (27 September), and the full line that on the following day when the two storms occurred. A positive temperature difference, as seen in the early morning hours, indicated a downward sensible heat flux from the warmer atmosphere above, suggesting that the radiant input at this time is insufficient to support the losses through longwave radiation and possibly evaporation. The humidity differences are always negative and indicate an upward flux of latent heat, that is, evaporation. When the storm occurred at 15:00, on 28 September, the temperature underwent a dramatic reversal and the humidity differences were significantly increased. Presumably the wet canopy was evaporating water at at a rate which could not be supported by radiation alone so that it drew energy from the atmosphere, causing local advection, and from the forest storage as suggested in Figure 3.

Hourly computations of energy balance assuming no horizontal temperature gradients, that is, no advection term, can be therefore quite erroneous in the presence of these small rainshowers. Convective cells of equivalent diameter smaller than, say, 5 km are common in the Amazonian forest and may introduce a serious problem of surface heat source heterogeneity which is impossible to solve with a single tower setup.

8.5 - CONCLUDING REMARKS

This work reports the first field campaign of a micrometeorological experiment in an Amazonian rainforest near Manaus. Most of the results presented here were published in Shuttleworth et al. (1984a, b and c).

The analysis of energy partitioning showed that about 75 percent of this energy is consumed in evapotranspiration and the remaining 25 percent in heating the air on dry days. In the energy balance equation it was assumed that, by integrating the fluxes over a daily cycle, both storage and net horizontal energy advection terms were zero. This balance may not be true, particularly on occasions when short duration rainshowers are presented. These convective cells have an equivalent diameter smaller than 5 km. If the rainshower is at the tower site, the forest surface acts as a sink of both sensible heat and storage energy which are used for evaporation. There should be a horizontal convergence of sensible heat at the tower site to supply this energy deficit. On the other hand, if the rainshower is elsewhere but near the tower, the reverse occurs and the air layer over the tower site should give a net horizontal divergence of sensible heat. On a daily basis, the evaluation of variation of energy storage in the forest and the net horizontal energy advection terms is a difficult task using only one tower. The assumption of horizontal homogeneity of the surface with respect to sources and sinks is questionable.

The analysis of wind profiles near neutral conditions gave values for the surface aerodynamic roughness and zero-plane displacement which are in agreement with other published results for temperate forests. The values of friction velocity computed with a mass conservation method were higher than expected and exceeded the values measured with the eddy correlation system by a factor of two. It was observed that the mean wind flow in the air layer above the site is generally weak, from the ENE-ESE quadrant. Sometimes the presence of a single convective cell to the west of the tower is sufficient to reverse the flow direction. There are other occasions when deep penetration of frontal systems into the tropics enhances the wind field during several hours. This was the case of 26 September when a frontal system was observed to the South of the Amazon Region.

One of the most controversial points is the influence that forests exert on climate. For the Amazon Region as a whole, Molion (1976) and Salati et al. (1979) have shown that on the average, 50 percent of the precipitation is recycled back into the atmosphere through evapotranspiration. The present analyses indicated that during the 25 days of September, 48 percent of the rainfall returned to the atmosphere as evapotranspiration. Of this, 17 percent was due to evaporation of intercepted rainfall by the canopy. Nowadays, man has acquired a great ability to transform the geography of large land masses, particularly through the removal of natural forests. Scientific studies have indicated that deforestation usually reduces evaporation locally. Since in the Amazon the local source of water vapour for precipitation is, on the average, of the same magnitude as the net advected vapour, a reduction of evaporation would reduce the regional precipitation. Furthermore Nobre (1983) remarks that a decrease in evaporation over land is nearly balanced by an increase in sensible heat flux. Sensible heat, however, warms the air only in a relatively shallow layer whereas the latent heat heats up the entire troposphere through the condensation of vapour in tall cumulus clouds. He concludes by stating that a large scale deforestation in the Amazon basin would affect the global weather and climate patterns due to changes in the planetary-scale tropical circulations which are forced by tropical latent heating and also changes in the subtropical jet stream which links tropical and extratropical circulations.

There is an urgent need to quantify the interaction between the Amazon forest and the atmosphere, especially concerning the latent heating of the atmosphere, and to model possible climate changes resulting from a large scale deforestation. The micrometeorological experiment near Manaus is a contribution to this effort.

8.6 - ACKNOWLEDGEMENTS

The author would like to thank his British colleagues W. J. Shuttleworth, J. H. C. Gash, C. R. Lloyd, C. J. Moore, J. M. Roberts, D. D. McNeil and H. R. Oliver and his Brazilian colleagues L. F. Aguiar, O. M. R. Cabral, G. Fisch, A. O. Marques Filho, J. C. Moraes, C. A. Nobre, S. Patel, M. N. G. Ribeiro, L. D. A. Sá, V. P. Silva Filho and A. O. Manzi, who worked diligently and contributed to make this micrometeorological experiment a reality. He also wishes to thank the following British Institutions: the Institute of Hydrology, the Natural Environment Research Council and the British Council; and the following Brazilian Institutions: the National Research Council (CNPq) and its affiliated institutes INPA and INPE, the Brazilian Company for Agricultural Research (EMBRAPA), through its National Research Center CNPSD, and the University of Amazonas. Financial support was provided by the above-mentioned institutions and is greatly acknowledged. Special thanks to his colleague C. A. Nobre who kindly reviewed this manuscript and Sueli A. F. V. Camargo Pinto for the expert typing.

8.7 - REFERENCES

FEDERER, C. A. Spatial Variation of Net Radiation, Albedo and Surface Temperature of Forests. *Jour. Appl. Met.*, 7: 789-795, 1968.

FRANKEN, W.; LEOPOLDO, P. R.; MATSUI, E.; RIBEIRO, M. N. G. Interceptação das Precipitações em Floresta Amazônica de Terra Firme. *Acta Amazônica*, 12 (3): 15-22, 1982.

GASH, J. H. C.; STEWART, J. B. The Average Surface Resistance of a Pine Forest Derived from Bowen Ratio Measurements. *Bound. Lay. Met.*, 8: 453-464, 1975.

GOURDRIAAN, J, MICRO WEATHER Simulation Model Applied to a Forest. In: S. Halldin, ed. *Comparison of Forest Water and Energy Exchange Models.* Copenhagen, p. 47-57, 1979. International Society of Ecological Modelling.

HEUVELDOP, R. The International Amazon MAB Rainforest Ecosystem Pilot Project at San Carlos de Rio Negro: Micrometeorological Studies. In: ADISOEMARTO, S.; BRUNIG, E. F., eds. *Transactions of the Second International MAB-IUFRO Workshop on Tropical Rainforest Ecosystem Research.* Hamburg, Reinbeck, 1979.

JACKSON, I. J. Problems of Throughfall and Interception under Tropical Forest. *J. Hydrol.*, 12 (3): 234-254, 1971.

JORDAN, C. F.; HEUVELDOP, J. The Water Budget of an Amazonian Rainforest. *Acta Amazônica*, 11 (1): 87-92, 1981.

McNEIL, D. D.; SHUTTLEWORTH, W. J. Comparative Measurements of the Energy Fluxes Over a Pine Forest. *Bound. Lay. Met.*, 9: 297-313, 1975.

MOLION, L. C. B. A Climatonomic Study of the Energy and Moisture Fluxes of the Amazonas Basin with Considerations of Deforestation Effects. INPE-923-TPT/035. São José dos Campos, 1976.

MOLION, L. C. B.; MOORE, C. J. Estimating the Zero-plane Displacement for Tall Vegetation Using a Mass Conservation Method. *Bound. Lay. Met.*, 26: 115-125, 1983.

MOORE, C. J. On the Calibration and Temperature Behaviour of Single-beam Infrared Hygrometers. *Bound. Lay. Met.*, 25: 245-269, 1983.

NOBRE, C. A. The Amazon and Climate. In: CLIMATE CONFERENCE FOR LATIN AMERICA AND THE CARIBBEAN, Geneve, Switzerland. *Proceedings*. (WMO Nº 632), 1983.

OGUNTOYINBO, J. S. Reflection Coefficients of Natural Vegetation Crops and Urban Surfaces in Nigeria. *Q. Jour. Roy. Met. Soc.*, 96: 430-441, 1970.

PINKER, R. T., THOMPSON, O. E.; ECK, T. F. The Albedo of a Tropical Evergreen Forest. *Q. Jour. Roy. Met. Soc.*, 106: 551-558, 1980.

READ, R. G. Microclimate as Background Environment for Ecological Studies of Insects in a Tropical Forest. *J.*

Appl. Met., 16 (12): 1282-1291, 1977.

SALATI, E.; DALL'OLIO, A.; MATSUE, E.; GAT, J. R. Recycling of the Water in the Brazilian Amazon Basin. *Wat. Res. Res.*, 15 (5): 1250-1258, 1979.

SPITTLEHOUSE; BLACK, T. A. Evaluation of the Bowen Ratio/ Energy Balance Method for Determining Forest Evapotranspiration. *Atmosphere-Ocean*, 18 (2): 98-116, 1980.

STEWART, J. B.; THOM, A. S. Energy Budgets in Pine Forest. *Q. Jour. Roy. Met. Soc.*, 99: 154-170, 1973.

SHUTTLEWORTH, W. J.; McNEIL, D. D.; MOORE, C. J. A Switched Continuous-Wave Sonic Anemometer for Measuring Surface Heat Fluxes. *Bound. Lay. Met.*, 23: 425-448, 1982.

SHUTTLEWORTH, W. J.; GASH, J. H. C.; LLOYD, C. R.; MOORE, C. J.; ROBERTS, J.; MARQUES FILHO, A. O.; FISH, G.; SILVA FILHO, V. P.; RIBEIRO, M. N. G.; MOLION, L. C. B.; NOBRE, C. A.; SÁ, L. D. A.; CABRAL, O. M. R.; PATEL, S. R.; MORAES, J. C. Observation of Radiation Exchange Above and Below Amazonian Forest. *Q. Jour. Roy. Met. Soc.*, (11): 1163-1169, 1984a.

——— Eddy Correlation Measurements of Energy Partition for Amazonian Forest. *Q. Jour. Roy. Met. Soc.*, (110): 1143-1162, 1984b.

——— *Daily Variations of Temperature and Humidity within and Above Amazonian Forest.* São José dos Campos, INPE, 1984c. (INPE-3196-PRE/559). Submitted to *Weather*.

THOMPSON, N. Turbulence Measurements above a Pine Forest. *Bound. Lay. Met.*, 16: 293-310, 1979.

FIGURE CAPTIONS

Figure 1 The mean value of radiation components above Amazonian rain forest for six days of continuous data (Shuttleworth et al., 1984a).

Figure 2 The mean values of (a) solar and (b) net radiation above and beneath the canopy of an Amazonian rain forest for six days of continuous data. Above-and below-canopy fluxes are plotted on different scales in each case. The bars indicate the standard error for each flux (Shuttleworth et al., (1984a).

Figure 3 Daily variation in measured net radiation, latent and sensible heats for eight fine days in Amazonian forest during September 1983. Thick line indicates net radiation; latent and sensible heat fluxes are shown as lightly shaded and darkly shaded portions respectively (Shuttleworth et al., (1984b).

Figure 4 Schematic diagram illustrating the height of the aspirated wet and dry bulb psychrometer systems mounted on the tower and their relationship to the forest canopy (Shuttleworth et al.,1984c).

Figure 5 Daily variation in temperature, humidity and humidity deficit measured at five heights through and just above the forest canopy, together with the above-canopy rainfall measurement for two days 27 and 28 September 1983 (Shuttleworth et al., (1984c).

Figure 6 Differential gradients of temperature and humidity measured above the forest canopy for daylight hours of 27 (broken line) and 28 September 1983 (full line), together with the above canopy rainfall measurement (Shuttleworth et al., 1984c).

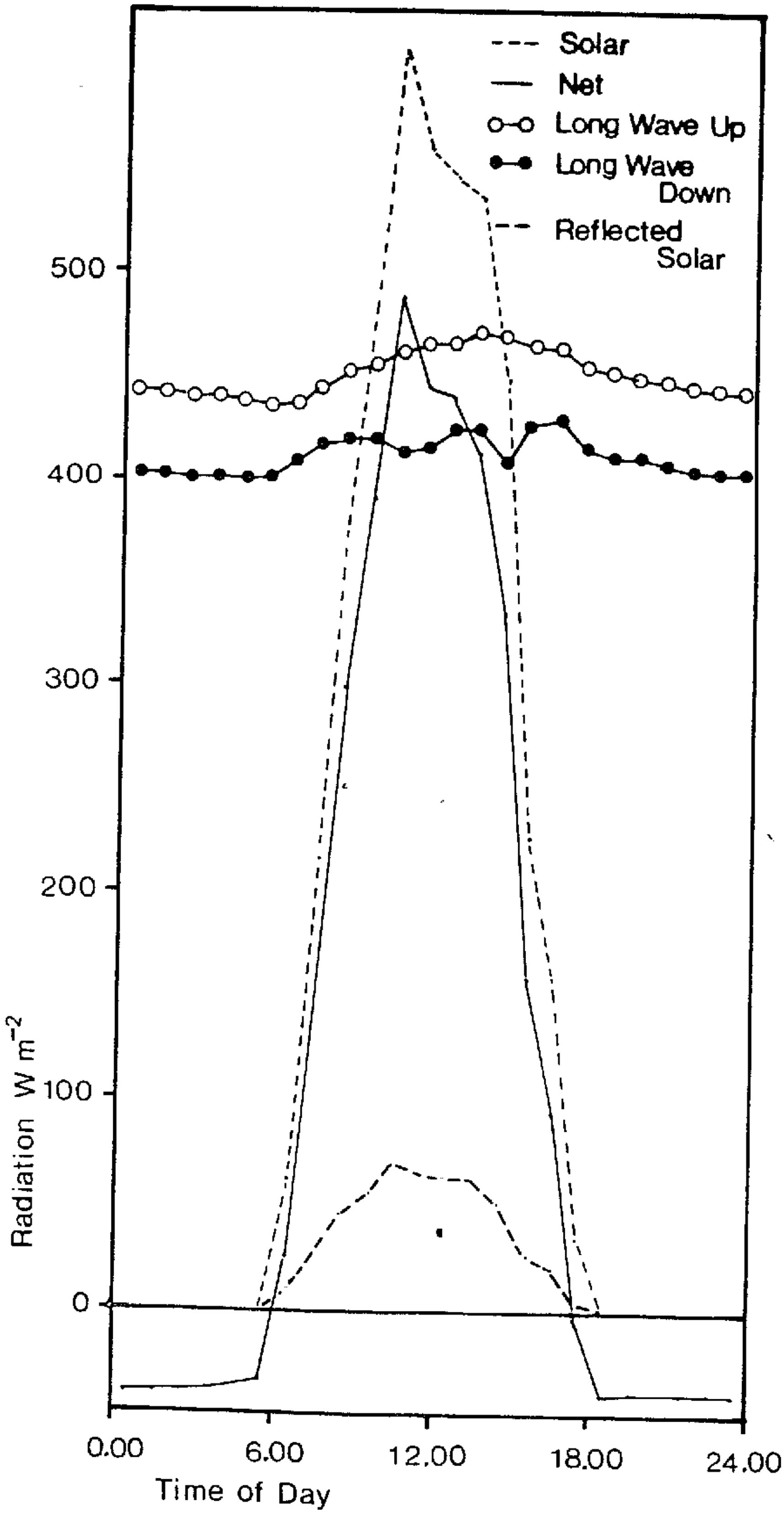
Solar
Net
Long Wave Up
Long Wave Down
Reflected Solar
Radiation W m^{-2}
0
100
200
300
400
500
0.00
6.00
12.00
18.00
24.00
Time of Day

Fig. 1

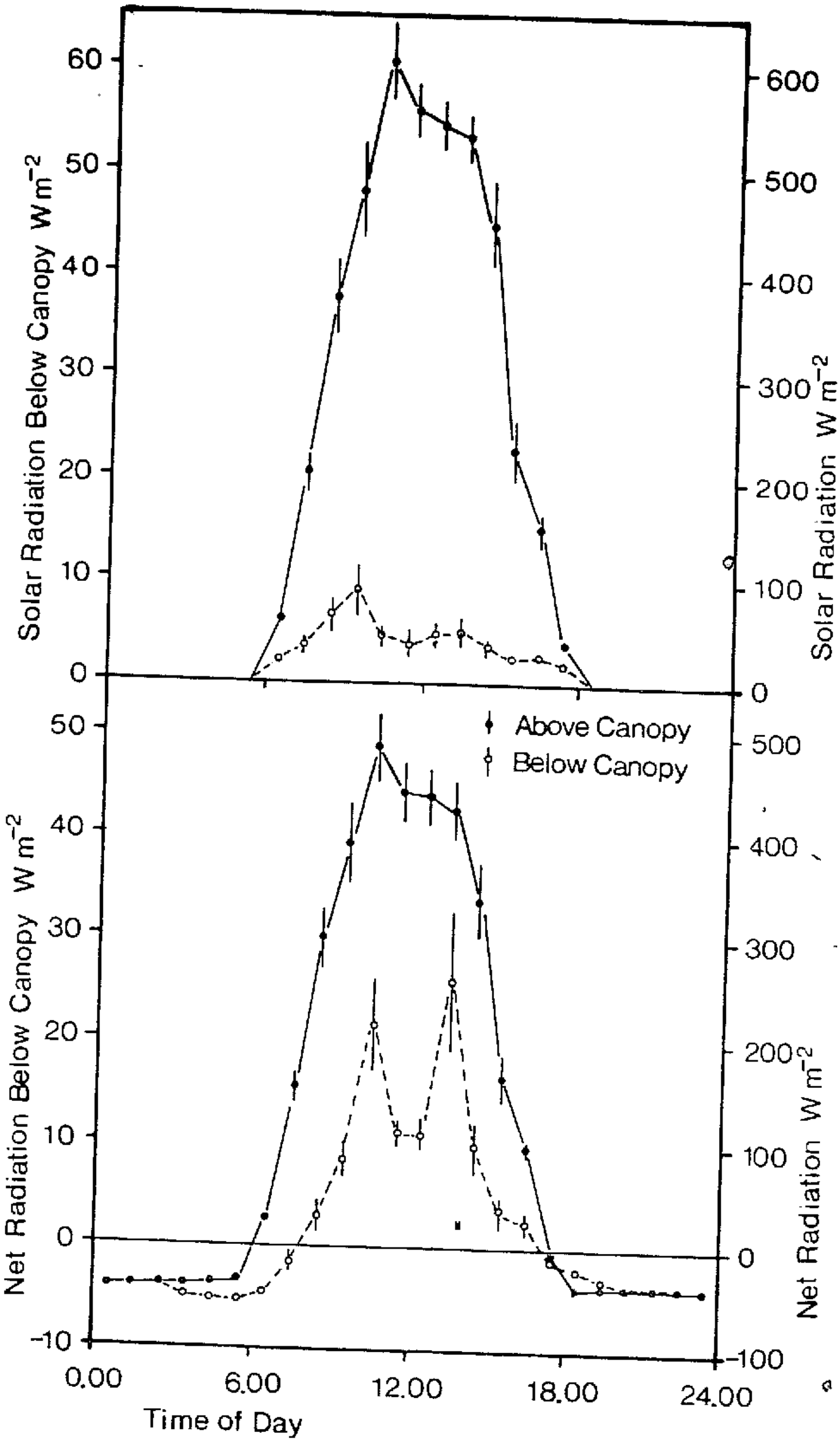
Solar Radiation Below Canopy W m-2
60
50
40
30
20
10
0
600
500
400
300
200
100
0
Solar Radiation W m-2
Above Canopy
Below Canopy
Net Radiation Below Canopy W m-2
50
40
30
20
10
0
-10
500
400
300
200
100
0
-100
Net Radiation W m-2
0.00
6.00
12.00
18.00
24.00
Time of Day

Fig. 2

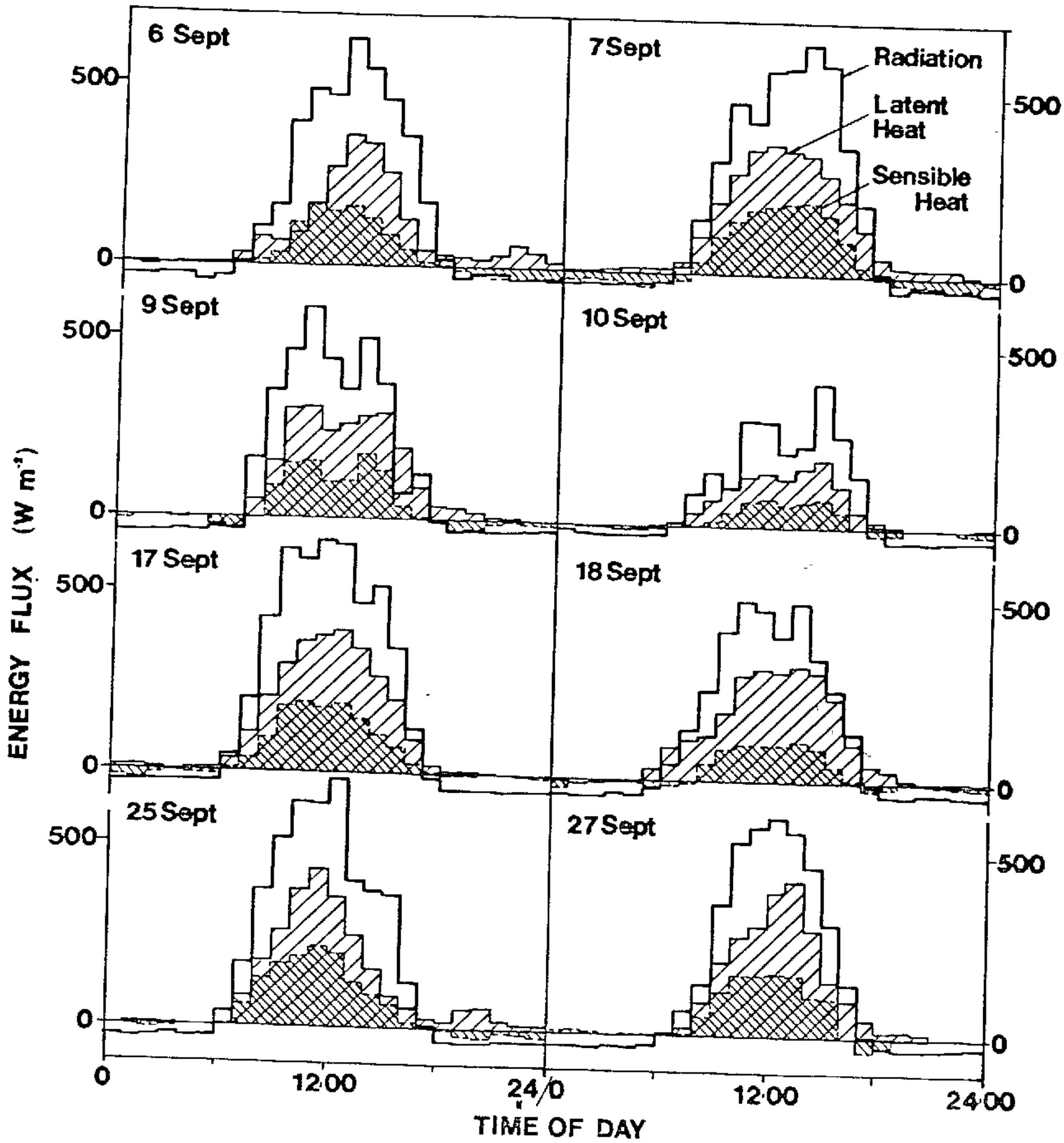
6 Sept
7 Sept
9 Sept
10 Sept
17 Sept
18 Sept
25 Sept
27 Sept
Radiation
Latent Heat
Sensible Heat
500
0
ENERGY FLUX (W m⁻²)
0
12:00
24/0
12:00
24:00
TIME OF DAY

Fig. 3

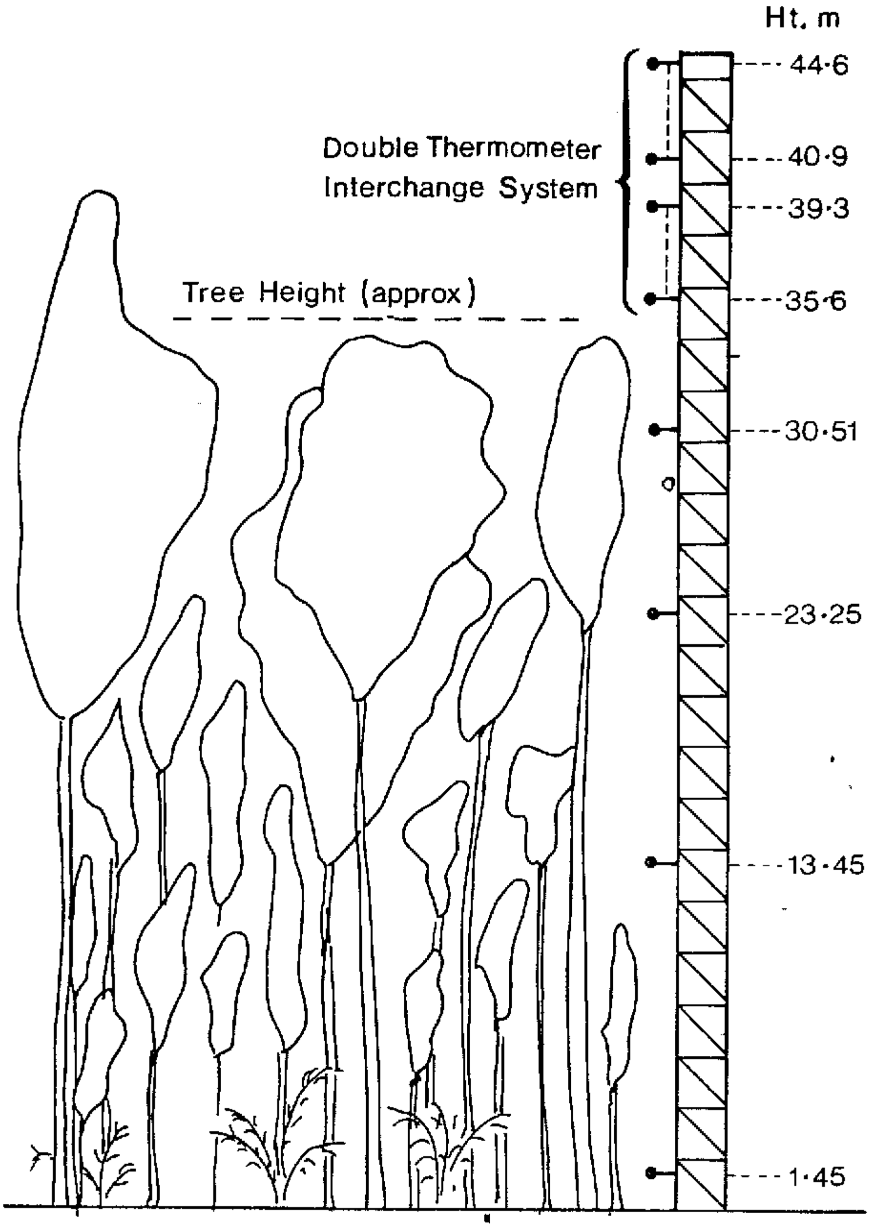
Ht. m
44·6
40·9
39·3
35·6
30·51
23·25
13·45
1·45
Double Thermometer
Interchange System
Tree Height (approx)

Fig. 4

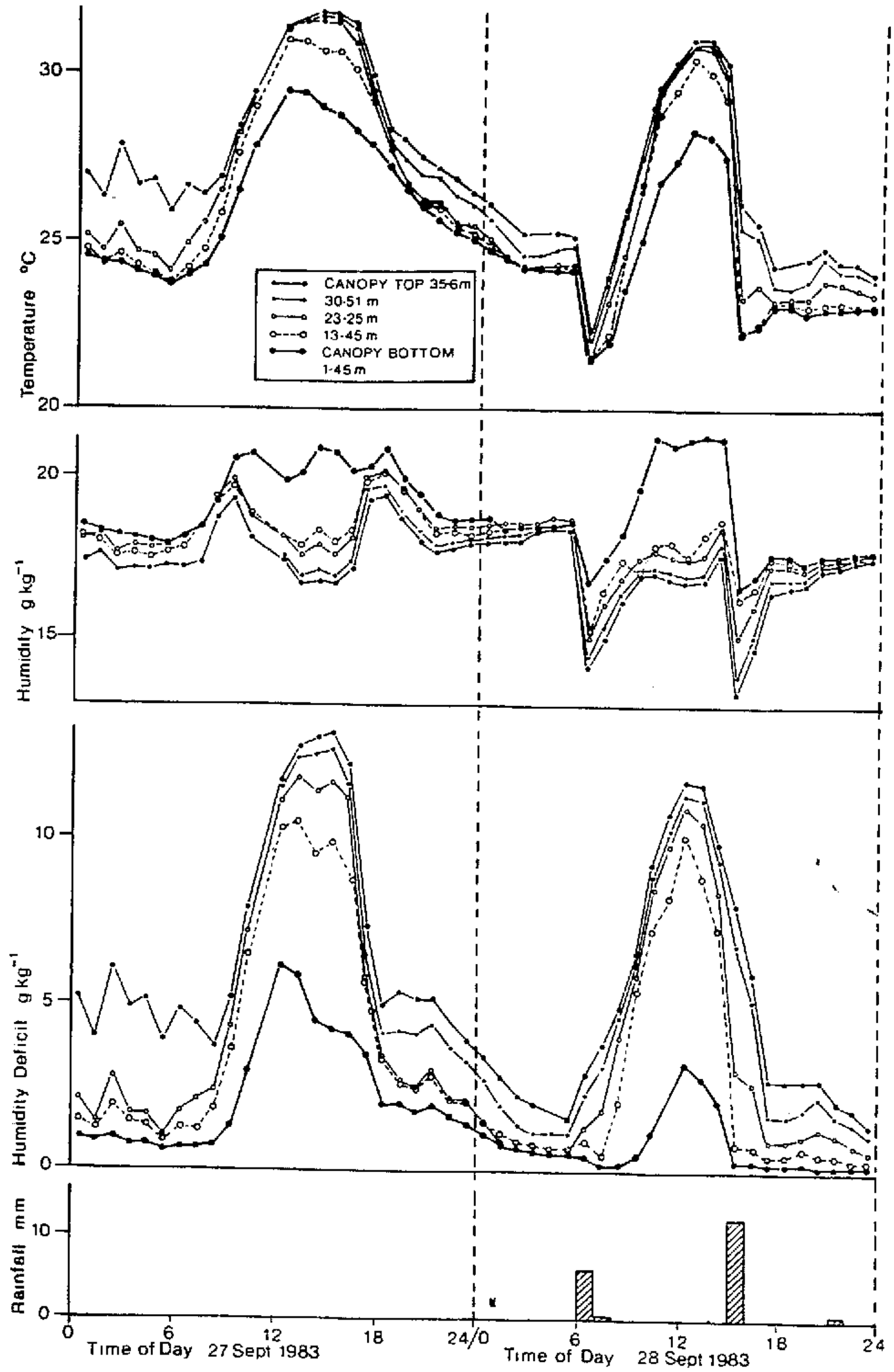
30
25
20
Temperature °C
CANOPY TOP 35·6m
30·51 m
23·25 m
13·45 m
CANOPY BOTTOM
1·45 m
20
15
Humidity g kg⁻¹
10
5
0
Humidity Deficit g kg⁻¹
10
0
Rainfall mm
0
6
12
18
24/0
6
12
18
24
Time of Day 27 Sept 1983
Time of Day 28 Sept 1983

Fig. 5

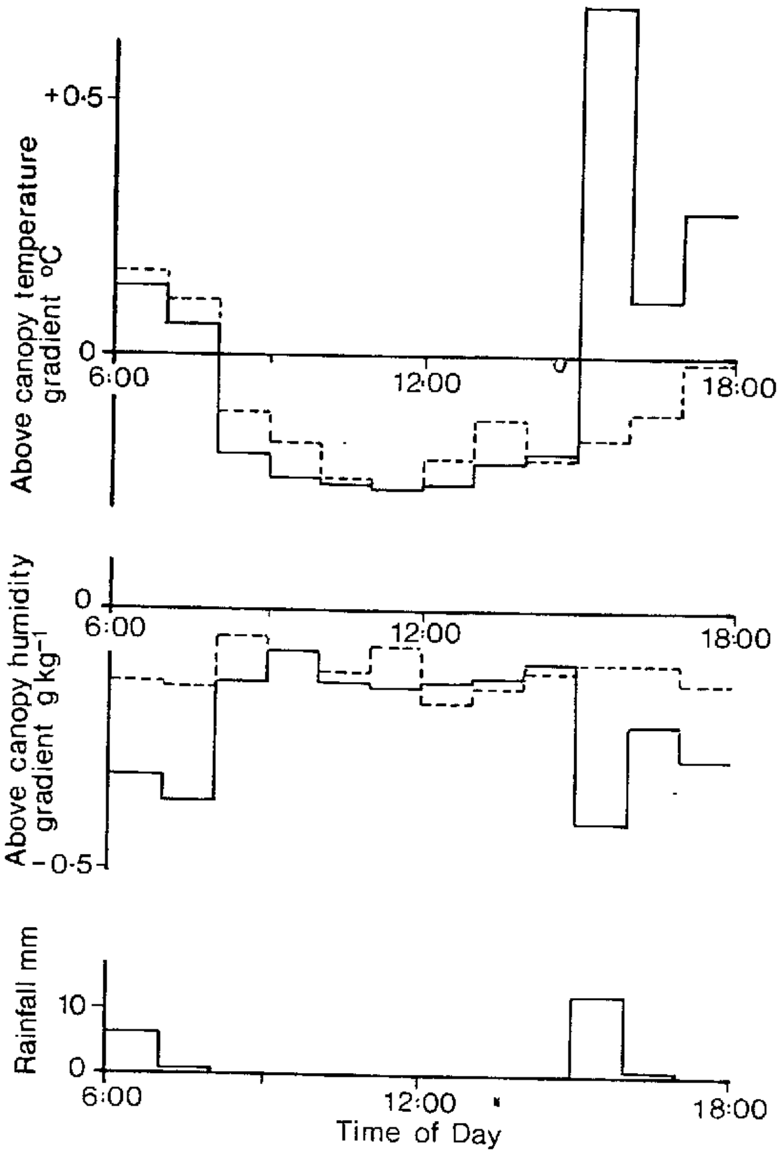
+0·5
0
6:00
12:00
18:00
Above canopy temperature gradient °C
0
6:00
12:00
18:00
Above canopy humidity gradient g kg⁻¹
-0·5
Rainfall mm
10
0
6:00
12:00
18:00
Time of Day

Fig. 6