Observations of radiation exchange above and below Amazonian forest

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SUMMARY

Measurements of shortwave and longwave components of the radiation budget were made above and below tropical forest in the Amazon Basin for a total duration of 203 hours in September 1983. Albedo was (12.25±0.2)% and showed a small variation with solar altitude. The net outward flux of longwave radiation was around 30 W m⁻², and fairly constant over the day. The relationship between net radiation, R, and solar radiation, S, was adequately described by the expression R = (0.858±0.006)S - (35.0±1.9) (W m⁻²). The fraction of solar radiation reaching the bottom of the canopy was low, about one per cent; net radiation in this position was consistent with low soil heat flux and low soil evaporation.

1. INTRODUCTION

Increasing awareness in recent years that the energy balance of extensive areas of tropical rain forest could be important to weather patterns on a global scale highlights the need for more comprehensive information on the radiation exchange of this vegetation type. Published results in this area are sparse, generally limited to particular aspects such as albedo (e.g. Oguntuyinbo 1970; Pinker et al. 1980; Pinker 1982). The Amazon basin is recognized as especially important in the context of global meteorology; in this paper we present radiation exchange data for this region. These results are the first from a more comprehensive micrometeorological study of Amazonian rain forest planned to comprise several intensive experimental sessions over several years. The data presented here were collected between 6 and 15 September 1983, and consist of 203 hours, including 6 complete days, of radiation measurements.

2. SITE AND INSTRUMENTATION

The experimental site is located at 2°57'S 59°57'W in the Reserva Florestal Ducke, 25 km from Manaus, Amazonas, Brasil. The surrounding forest is undisturbed, and ground-level vegetation below 1.2 m, the measurement height of the below-canopy radiometers, is scarce. Above this, vegetation extends with no obviously defined sub-stories to a height of 35 m, with occasional emergent trees reaching 40 m. The above-canopy instruments were mounted at a height of 45 m at the top of an aluminium scaffolding tower.

The weather during September 1983 was atypical of the climatological average at this location. Rainfall during the month was around 150 mm, which is significantly higher than the September climatological average of 60 mm (Ratisbona 1976). This abnormal weather influences the results as described in later discussion.

Two downward-facing Kipp solarimeters and two Funk-type net radiometers were used to provide the measurements of $S_R$, reflected solar radiation, and $R$, net radiation, respectively. These were mounted accurately level at the end of 3.5 m booms orientated approximately 30° west and 30° east of north. With this orientation there was no possibility of tower shade interfering with the measurements. The measurements produced by these pairs of instruments agreed within systematic errors of 3% or less; their respective mean values were used in the analysis.

Instruments of the same manufacture were used to provide the measurements of $S$, the incoming solar radiation above the canopy, and $S_{BC}$ and $R_{BC}$, the measurements of solar and net radiation beneath the canopy. The below-canopy radiometers were moved to new, randomly chosen, positions on alternate days. A unidirectional radiometer was mounted at the top of the tower to measure $U$, the total incoming radiation. In this instrument the lower plastic dome on a standard Funk-type net radiometer was replaced with an optically black, metal hemisphere, the temperature of which was measured with a calibrated thermistor. The radiation entering this modified radiometer from below is calculated from the temperature of the metal hemisphere, and in this way its output can be used to provide a measurement of the total incoming radiation entering from above. The downward flux of longwave radiation, $L_D$, and upward flux of longwave radiation, $L_U$, are derived from combinations of the measured fluxes (see section 3).

* Authors as in preceding paper (Shuttleworth et al., 1984, 110, 1143-1162).
All the radiometers used in this experiment have been used and recalibrated over ten years with a total change in calibration of about 1% over this time.

The data were recorded with a tape cassette logger system (Microdata, Radlett) with purpose-built interface cards designed to give a resolution better than 4 W m\(^{-2}\) on individual measurements. Twelve such measurements were made at five-minute intervals and these were combined to provide the hourly average values used in this analysis. In this way the digital noise in the measurement is reduced to around 1.5 W m\(^{-2}\). The recording system stores the individual measurements as truncated integers and is therefore subject to a systematic rounding error; a correction was made for this during analysis. Measurements of incoming solar radiation were drawn from initially one, and after 8 September two, automatic weather stations (Didcot Instruments, Abingdon), which use a similar logging system. These stations also provided the measurements of air temperature referred to in later discussion. Data collection ended prematurely on 15 September when the primary recording system was damaged during an overhead electrical storm.

3. NOMENCLATURE

\(L_D\) Calculated downward flux of longwave radiation, \(= U - S\) (W m\(^{-2}\))
\(L_U\) Calculated upward flux of longwave radiation, \(= U - R - S_R\) (W m\(^{-2}\))
\(R\) Measured flux of net radiation above the forest; mean value of two measurements (W m\(^{-2}\))
\(R_{BC}\) Measured flux of net radiation below the forest canopy; single measurement from randomly located sensor (W m\(^{-2}\))
\(S\) Measured flux of incoming solar radiation; initially a single measurement, after 8 September mean value of two measurements (W m\(^{-2}\))
\(S_R\) Measured flux of solar radiation reflected by the forest; mean value of two measurements (W m\(^{-2}\))
\(S_{BC}\) Measured flux of solar radiation below the forest canopy; single measurement from randomly located sensor (W m\(^{-2}\))
\(T_s\) Mean air temperature at screen height; measured with automatic weather station (K)
\(U\) Measured flux of total downward radiation; single measurement (W m\(^{-2}\))
\(\alpha\) Solar altitude angle (degrees)
\(c\) Mean cloudiness of the sky (as a fraction)
\(e_a\) Apparent emissivity of clear sky (per cent)
\(r\) Solar radiation reflection coefficient (albedo)
\(\sigma\) Stefan–Boltzmann constant, \(5.67 \times 10^{-8}\) (W m\(^{-2}\)K\(^{-4}\))

4. RESULTS

(a) Albedo

Data collection occurred near the date of maximum solar zenith and so provided an opportunity to study the variation in albedo over a broad range of solar altitude angles. The albedo \(r\) was calculated using hourly average values of incoming and reflected solar radiation and plotted against the hourly average solar altitude angle \(\alpha\). Hours when incoming radiation was less than 20 W m\(^{-2}\) or the mean reflected radiation less than 1 W m\(^{-2}\) were rejected; a total of 94 hours data remained.

The results occur as six groups, corresponding to the hours either side of midday, and are so presented in Fig. 1. Bars indicate the standard error of the albedo at each solar altitude angle; the numbers in brackets are the number of values in each group. Also shown in this figure is a second-order polynomial fit to the data, of the form

\[
r = 15.09 - 0.136\alpha + 0.00123\alpha^2
\]

which provides a good description of these particular data. The mean value of the albedo is 12.25 ± 0.2 at a mean solar altitude angle of 43.8°. This value is represented by the broken line.

(b) Above-canopy radiation flux components

Figure 2 describes the average diurnal variation of the shortwave and longwave components of the radiation flux and the net radiation for the six days for which continuous data are available. Random errors are reduced by the averaging process but systematic errors persist; it should be remembered that the longwave components are particularly sensitive to error since they are calculated as a combination of several measured fluxes.
Figure 1. The variation in solar radiation reflection coefficient (albedo) as a function of the solar altitude angle. Bars indicate standard errors: the full line is the second-order polynomial fit to the data described in the text, while the broken line is the mean value of albedo over all angles.

Figure 2 reveals that, on average, solar radiation peaks before midday and then falls slightly in the afternoon, presumably in response to increasing cloud cover. This behaviour is of course mirrored in reflected solar radiation and net radiation. Average net radiation is rather steady around $-40 \text{W m}^{-2}$ through the nighttime hours between 1800 and 0500, when upward and downward longwave radiation follow each other: their joint behaviour reflects the mean daily trend in air temperature over this period. During the day the longwave components continue to follow air temperature but the net longwave radiation loss decreases slightly around midday.

In view of these rather simple daily trends in average flux components and albedo, a strong and linear correlation is expected between solar and net radiation. Figure 3 demonstrates that this is so. In this figure the results have been sorted into 100 W m$^{-2}$ groups and are presented as mean values for each group together with the standard error and the number of values used in the average. The line of linear regression shown in this figure is given by

$$R = (0.858 \pm 0.006)S - 35.0 \pm 1.9$$

and has a correlation coefficient of -99. The albedo implicit in Eq. (2), in the order 14%, is slightly higher than, but consistent with, the mean albedo given in section 4(a). This apparent difference reflects the fact that in these data the daily cycle in $L_U$ is slightly greater than that in $L_D$. Monteith (1973, chapter 3) points out that "(such) behaviour is to be expected if changes in atmospheric temperature are governed by and follow changes in surface temperature"; but that "at other sites, $L_D$ appears to change more than $L_U$, for reasons which are not yet understood".

(c) Below-canopy flux

Figure 4 presents the above- and below-canopy fluxes of solar and net radiation in the form of hourly mean and standard error for the six days when continuous data were available. The percentage variability in the below-canopy fluxes is significantly greater than that in the above-canopy flux. This reflects the fact that these fluxes are subject to sampling errors which are caused by spatial variability and additional to the meteorological variability present in the above-canopy values. Moreover, below-canopy fluxes are rather a poor reflection of above-canopy behaviour in daylight conditions, indicating that the data represent a less than perfect spatial average. On average solar radiation reaching the ground is 1.2% of that above the canopy, i.e. an average flux of about 4 W m$^{-2}$ during the twelve daylight hours.

The daily trend of below-canopy net radiation lags behind that in the equivalent above-canopy flux, and provides an average positive input of around 0.06 MJ m$^{-2}$ over 24 hours, approximately equal to the input of solar radiation. The remaining radiation exchange, a daily cycle with an
hourly average in the order 4 W m\(^{-2}\) entering the soil during the day and leaving during the night, is consistent with separate measurements of soil heat flux not presented here. Such low values of radiation and soil heat flux are typical of dense forest vegetation (e.g. Oliver 1983).

When considering fluxes of this size it is important to remember that the magnitudes quoted are in the same order as the resolution and possible offset drift of the systems used to measure them, and that spatial variability here is high. Values quoted should be considered as orders of magnitude only; they could easily be subject to errors of 100%.

5. DISCUSSION

The average value of 12.25% for the albedo of Amazonian rain forest is consistent with the value of 13% reported by Oguntoyinbo (1970) for tropical forest in Nigeria, and 12% reported by Pinker et al. (1980) for tropical forest in South-east Asia. The small variation over the complete range of solar altitude in the data presented here contrasts with the results obtained by Pinker et al. in clear sky conditions, but is consistent with the behaviour they observe in overcast conditions. Mean cloudiness is generally high at this location, 0.66, and, as mentioned earlier, the weather conditions prevailing during this experiment were probably not typical of the climatological average for September. The rainfall was more typical of the rainy months (December to April) when mean cloudiness (\(c\)) is around 0.71, rather than September when it is around 0.61 (Ratisbona 1976).
Figure 3. The relationship between net radiation flux and incoming solar radiation measured above an Amazonian rain forest. Bars indicate a standard error for each group of data. The line is the line of best fit described in the text.

It is worth noting that changes in measured reflection ratio are very sensitive to experimental error, and are particularly sensitive to offset errors in logging systems at small solar altitudes. Perhaps it is fortunate that it is the average albedo calculated from integrated daily fluxes of incoming and reflected solar radiation which is important, since the redistribution of solar energy in the diurnal cycle, given by an altitude-dependent albedo, is easily masked in the total energy budget by energy storage in the forest.

The measured longwave radiation components in Fig. 2 merit some discussion. The mean upward component of longwave radiation, 452.1 W m\(^{-2}\), agrees well with an estimate of 451.6 W m\(^{-2}\), calculated assuming that mean surface temperature and mean measured air temperature at screen height \((T_a = 25.8^\circ C)\) are equal and that the surface emissivity equals one. The daily cycle shows similar agreement: calculations for 05 and 13h give estimates of 436.7 and 471.5 W m\(^{-2}\) respectively, which compare with mean measured values of 436.7 and 471.6 W m\(^{-2}\).

The downward longwave component is more difficult to describe although empirical formulae to estimate daily average values do exist. Monteith (1973) suggests two equations:

\[
L_D = (1 - c)\epsilon_a\sigma T_a^4 - c(\sigma T_a^4 - 9) \tag{3}
\]

and, for low cloud,

\[
L_D = \epsilon_a(1 + 0.2c^2)\sigma T_a^4 \tag{4}
\]

the nomenclature for which are defined in section 3. He further suggests that \(\epsilon_a\), the apparent emissivity of clear sky, can be estimated by a second pair of equations:

\[
\epsilon_a = 0.65 - 0.007(T_a - 273) \tag{5}
\]

and

\[
\epsilon_a = 0.53 + 0.06\sqrt{\epsilon} \tag{6}
\]

\(\epsilon\) being mean vapour pressure (mb). For the mean temperature \((25.8^\circ C)\) and mean vapour pressure \((26.5\text{ mb})\) applicable to the present data, Eqs. (5) and (6) give similar estimates of \(\epsilon_a\): 0.831 and 0.835 respectively. Equation (3) gives values of 417, 421 and 424 W m\(^{-2}\), and Eq. (4) values of 405, 409 and 415 W m\(^{-2}\), as estimates of \(L_D\) for cloudiness values 0.61, 0.66 and 0.71 mentioned earlier. The mean measured value of downward radiation given in Fig. 2 is 412 W m\(^{-2}\).
Figure 4. 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. Bars indicate the standard error on each flux.

The simple relationship between net radiation and solar radiation illustrated in Fig. 3 is an encouraging feature of these data. Empirical relationships of this last type are of particular significance in remote and sparsely populated regions, such as the Amazon basin, where remote sensing techniques are important. There is a clear need to extend such empiricism to other times of the year.

A further interesting aspect of these results is the ratio between the integrated solar radiation reaching the surface and that received at the top of the atmosphere. The average solar radiation input for the six complete days considered is 14.82 MJ m\(^{-2}\) which, using the tables given by Doorenbos and Pruitt (1977), is 40\% of extra-terrestrial radiation. Assuming cloudiness in the order 0.66 (5.3 oktas) this value is significantly less than that for humid equatorial highlands (48\%) (cf. Frére and Rijks 1974). This requires further investigation with more extensive data.

Below-canopy fluxes are extremely low in this environment; the fraction of solar radiation reaching the forest floor, about 1\%, contrasts with values in the order 14\% reported for pine forest (Stewart 1978). The difference is, however, consistent with anascope measurements of canopy cover at the two sites: 91\% and 74\% (Gash and Morton 1978) respectively. Such a low below-canopy fraction has been observed for dense plantations of Corsican pine (Oliver, H. R. and Oliver, S.A., 1982; personal communication) and is consistent with a measurement of 4\% reported by Snedaker (1970) for tropical forests in Guatemala. Assuming there is limited downward movement of sensible heat to the soil through the still air near the base of the canopy, the mean value of excess radiation reaching the ground during daylight hours (4 W m\(^{-2}\)) represents an order of magnitude estimate of possible soil evaporation.
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