Plant Ecology **153:** 215–229, 2001.

Modelling rainfall and canopy controls on net-precipitation beneath selectively-logged tropical forest

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Key words: ENSO, Interception loss, Time-series modelling, Variogram, Wet canopy evaporation

Abstract

Understanding spatio-temporal patterns in rainfall received beneath tropical forest is required for eco- hydrological modelling of soil-water status, river behaviour, soil erosion, nutrient loss and wet-canopy evaporation. As selective-logging of tropical forest leaves a very complex mosaic of canopy types, it is likely to add to the spatio-temporal complexity of this sub-canopy or net precipitation. As a precursor to addressing this problem, the analysis presented here will examine the two dominant biophysical controls on sub-canopy precipitation. These controls are: (a) the spatial and temporal patterns in above-canopy or gross rainfall, and (b) the rate of wet-canopy evaporation associated with each type of canopy structure created by selective-forestry. For this study, over 400 raingauges were installed within a 10 km^2 area of lowland dipterocarp forest affected by selective-forestry some 9-years prior to this work. Gauges were located beneath various canopy types and within large openings. The spatial distribution of gross rainfall (monitored within the openings) was modelled using variography, while the effects of different canopy types on sub-canopy preciptation was analysed by comparing 6-month totals. The temporal distribution of gross rainfall over an 11-year record collected at the same site (Danum Valley Field Centre) was modelled with Data-Based-Mechanistic (DBM) approaches. These DBM approaches were also applied to the rainfall time-series of the two adjacent meteorological stations; all three gauges being contained within a 5000 km^2 region of Eastern Sabah in Malaysian Borneo.

Strong diurnal modulation was apparent within gross rainfall for the inland rainforest site, with a distribution consistent with a dominance of local convective rain cells. A similarly strong cycle coincident with the periodicity of the El Niño-Southern Oscillation (ENSO) was present within all of the region's rainfall records, though marked differences in annual and intra-annual seasonality were apparent. The preliminary variogram modelling indicated that a deterministic drift was present within the local-scale gross rainfall data, probably related to local topographic effects. Notwithstanding the need to remove this drift, the work indicated that spatial models of gross rainfall could be identified and used to interpret similar models of net-precipitation. During the ENSO drought-period monitored, the lowland dipterocarp forest allowed 91% of the gross rainfall to reach the ground as throughfall. These rates were, however, reduced to between 80%–86% beneath representative plots of moderately impacted to creeper-covered, highly damaged patches of forest.

Introduction

Tropical forest canopies modify the spatial and temporal distribution of rainfall before it reaches the ground. A component of the rainfall never reaches the ground, because the water intercepted by leaves, branches and stems evaporates by a process called 'wet-canopy-evaporation' or 'interception-loss'. A further component temporarily stored by the canopy will then drip from canopy surfaces as 'leaf-drip', or be channelled down tree stems as 'stemflow'. The remaining component of rainfall will drop through small gaps

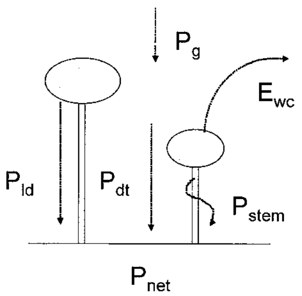

Figure 1. Schematic diagram of the interaction between tropical forest canopies and received rainfall. Symbol P_g is the gross precipitation (i.e., water received above the forest canopy or in large gaps between different tree canopies), P_{net} is the net precipitation (i.e, water received by the forest floor beneath a canopy), P_{ld} is the leaf-drip component of the net precipitation, P_{dt} is the direct throughfall component of the net precipitation (i.e, the raindrops penetrating the canopy that do not hit leaves, branches or stems of trees), P_{stem} is the stemflow component of the net precipitation and E_{wc} is the wet-canopy evaporation.

in the canopy as 'direct-throughfall' (Figure 1). The total volume and spatio-temporal distribution of rainfall reaching the ground, called 'net precipitation' or 'sub-canopy rainfall' (P_{net}), is, therefore, not only dependent on (a) the amount and distribution of the rainfall received by the canopy (Lloyd 1990), but also on (b) the structure of the canopy itself (Herwitz 1985).

Localised removal of trees as part of commercial, selective forestry is common within the rain forests of the Eastern Tropics (Whitmore 1998). Disturbance to the canopy structure as a result of the selective removal of trees will affect the amount and distribution of net-precipitation by changes to (i) the canopy storage and sub-canopy pathways, and (ii) the efficiency of the wet-canopy-evaporation (E_{wc}) process. Quantifying E_{wc} rates is important to understanding the development of small-scale convective rainfall cells and hence to the local cycling of water (Shuttleworth 1988) but may also play a role in macro-scale processes described within Global Circulation Models (Riehl 1954; Henderson-Sellers et al. 1993). Indeed, one theory controversially places the upward flux of water vapour above equatorial Southeast Asia as one of the main driving forces in global circulation (Newell & Gould-Stewart 1981)

Losses or additions of water to catchments as a result of forestry impacts on E_{wc} have equally important implications for local water resources and nutrient losses (Bruijnzeel 1990). As the tropical environment may experience a significant proportion of its rainfall within highly localised and intense convective cells, accurate modelling of soil moisture, river generation or soil erosion requires estimates of water input to a high spatial and temporal resolution (Brooks & Spencer 1995; Chappell et al. 1998, 1999a, b; Calder 2001). As a consequence, provision of detailed data on the spatio-temporal structure of sub- canopy rainfall becomes important to the understanding of patterns of plant water-stress, aquatic ecology and nutrient pathways (Bruijnzeel 1990; Eschenbach et al. 1998; Martin-Smith 1998).

While there are clear reasons for understanding P_{net} (and its controls) within tropical rain forests, its magnitude and spatio-temporal structure are difficult to quantify, particularly within selectively harvested areas. This is because of (a) the relative importance of highly localised convective rainfall cells in the tropics (Riehl 1954), and (b) the 'patchiness' of the different canopy forms produced by selective forestry, giving locally variable E_{wc} rates (Asdak et al. 1998). The dearth of published studies on the spatio-temporal structure of sub-canopy rainfall and its controls within selectively-disturbed forest also adds to the complexity of the problem. As a result, this study focuses on selectively-logged forest, and is the first stage in a more comprehensive analysis of sub-canopy rainfall (Bidin, in preparation). The specfic aim of this initial analysis is to address the key spatio-temporal controls on sub-canopy rainfall of (a) the temporal structure of gross rainfall over the short- and long-term, (b) the spatial structure of gross rainfall over the scale of a typical 'experimental research catchment' (i.e., 0.5–10 km^2), and (c) the time-averaged differences in P_{net} between the different 'canopy types' produced by selective forestry.

Study areas

The rain forest site chosen for study lies close to the Danum Valley Field Centre or 'DVFC' (4°58′ N and 117°48′ E) in the Malaysian state of Sabah, Borneo Island (Figure 2). The area lies within the Ulu Segama Forest Reserve, where the Forestry Upstream Division of Yayasan Sabah manage the forest for commercial timber production and conservation. The selective forestry management system adopted within this forestry concession is typical of that practiced within other concessions of Southeast Asia (Pinard & Putz 1996). The DVFC locality formed the focus of the rainfall analysis, as river- and sediment-generation processes within a series of experimental catchments

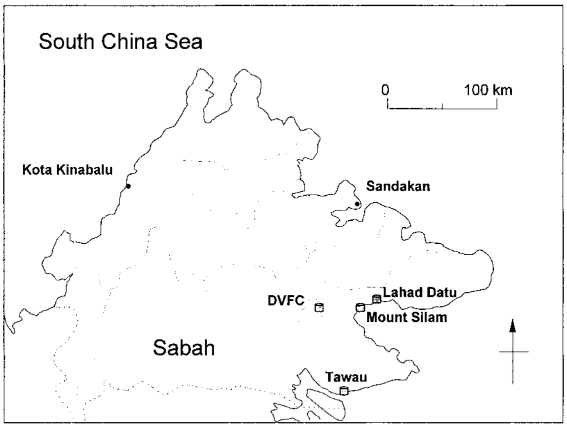

Figure 2. Location of the Danum Valley Field Centre (DVFC), Lahad Datu, Mount Silam and Tawau rainfall stations in Sabah, Malaysian Borneo.

have been studied here since 1986 (Douglas et al. 1992, 1999). Moreover, recent hydrological modelling of these data (Chappell et al. 1998, 1999a) would benefit from a better understanding of the spatio-temporal controls on the rainfall received below the forest canopy.

Regional scale

Daily rainfall has been measured at the DVFC meteorological station since 1986, and over the 13-year monitoring period (1986–1998) an average annual rainfall (*AAR*) of 2663 mm (409 mm σ) has been recorded. The DVFC rainfall study (Bidin in preparation) was undertaken over a 'water-year' 1 May 1997 to 30 April 1998 which covered the two driest calendar-years on record. In 1997 only 1921 mm rainfall or 72% *AAR* was recorded, and only 2130 mm (80% *AAR*) in 1998. The DVFC meteorological station (149 m a.s.l.) is important as it is one of the few stations within the interior of Malaysian Borneo providing records to the Malaysian Meteorological Service (MMS or Perkhidmatan Kajicuaca Malaysia). The nearest long-term rainfall stations to DVFC are Lahad Datu Airport 60 km to the east, and Tawau Airport 83 km to the south southeast. Some rainfall records are also available from Silam Camp (10 m a.s.l.) and Mount Silam (884 m a.s.l.) which are 47 and 43 km directly east of DVFC, respectively (Bruijnzeel et al. 1993). These four stations are all located on the East coast of Sabah (Figure 2). Automatic raingauges have been installed within the DVFC locality and some preliminary analysis has been undertaken by Sherlock (1997). He found that high rainfall intensities are relatively frequent with rates in excess of 4.167 mm/5-min (50 mm h^{-1} equivalent) having a return-period of 23.3 days and in excess of 8.333 mm/5-min (100 mm h^{-1} equivalent) a return-period of 139.6 days.

Local scale

A 10 km^2 area by DVFC was chosen as the focus for local-scale, spatial analysis of above- and below-canopy rainfall. This area has an undulating topography with an altitudinal range from 155 m (Sapat Kalisun river) to 435 m (Bukit Atur) and is covered by 'lowland dipterocarp rain forest' (Newbery et al. 1992) logged during 1988–1989. Timber extraction was by a 'selective', rather than a 'clearfell', logging system where only commercial timber trees with a girth greater than 0.6 m were felled. This type of selective silvicultural system produced a mosaic of 'canopy types'. Bidin (in preparation) has classified these 'patches' of different canopy into:

- Category 1: undisturbed forest canopy,
- Category 2: moderately impacted forest canopy,
- Category 3: very disturbed and climber-covered canopy,
- Category 4: cleared areas now dominated by *Macaranga* spp. pioneer trees,
- Category 5: cleared areas now supporting only shrubs, herbs and sprawling plants, and
- Category 6: no canopy.

These classes were chosen as (i) they could be easily identified by ground survey (with only limited experience), (ii) their expected differences in wet-canopy-evaporation rates (Asdak et al. 1998), and (iii) their importance to foresters in the estimation of future timber yields. Category 1 includes patches of virgin (protected) forest in 'riparian buffer zones' or in areas where slope angles are in excess of 30 degrees (Pinard & Putz 1996). Category 2 forest patches are those areas where the selective removal of commercial timber trees by tractor yarding has not severely damaged the remaining canopy. Category 3 forest is found in areas affected by 'high-lead' timber extraction (Conway 1982) where the remaining trees are severely damaged and have become covered in woody climbers typically of the *Merremia*, *Mezoneuron* and *Uncaria* spp. (Whitmore 1998). This type of high-impact yarding is now banned within the Yayasan Sabah forestry concession. Category 4 areas have been colonised by *Macaranga* spp. pioneer trees and are typically found in the 40 m-wide road corridors where ‘Matahari clearance’ (Conway 1982) has taken place. Such roadside clearance is undertaken to aid road drying and hence trafficability for haulage lorries. Some of the rotational landslides (ca. 0.5 to 5 ha) developed along these haulage roads have also been colonised by *Macaranga* spp. trees (Chappell et al. 1999b), though others only support category 5 vegetation. Where high-lead logging or Matahari clearance has removed all trees and *Macaranga* spp. pioneer trees have failed to colonise then only the shrubs (notably Zingiberaceae), herbs and sprawlers of category 5 canopy are found. Category 6 areas lack a vegetation canopy and are associated with gravel-surfaced haulage roads or highly compacted dirt roads, ‘skid trails’ or ‘log-landings’ (Conway 1982). This study aimed to examine the above- and sub-canopy rainfall associated with forest patches clearly within one of these canopy classes.

Instrumentation and monitoring

For the initial identification of temporal structures in above-canopy rainfall, daily records monitored at the DVFC, Lahad Datu and Tawau meteorological stations were compared. An 11-year time-series (i.e., 1 January 1986 to 31 December 1997) for DVFC was used, while $14\frac{1}{2}$-year (i.e., 1 January 1982 to 23 June 1997) and 17-year (i.e., 1 January 1980 to 31 December 1997) records were used from Lahad Datu and Tawau, respectively. Measurements had been made with UK Meteorological Office Mark II daily storage gauges sited away from obstructions and with the gauge orifice at 0.3 m above the local ground-surface, but lacking any turbulence protection. The diurnal rainfall distribution at the DVFC locality utilised data collected from a single tipping-bucket raingauge (Station name: ‘km63’) over the 3-year period from 1 January 1995 to 31 December 1997. The ‘km63’ raingauge, a Casella W5724 tipping-bucket collector, was sited on an outcrop of chert (site photograph in Whitmore 1998, Figure 7.24) and at 20 m from the nearest trees.

For the initial analysis of the spatial structure of above-canopy rainfall, a network of 34 storage gauges located within the 10 km^2 area East of DVFC was used. These gauges formed part of a larger network of 50 gauges for above-canopy rainfall measurement, and a further 345 gauges for sub-canopy measurement. These storage gauges incorporated funnels with a 0.15 m diameter orifice, sited 0.56 m above the ground and having a drop of 0.23 m to the funnel base to prevent ‘out-splash’. Evaporation losses from the 5 dm^3 plastic collection bottles were reduced by (a) directing the flow through narrow diameter holes in the funnel base, and (b) painting the gauges white to reduce radiation absorption. The whole gauge was held exactly vertical by attachment to a wooden stake. The accuracy of these non-standard gauges was extensively tested (Bidin in preparation). In one experiment, catch error was estimated by comparing the results of 10 non-standard gauges sited adjacent to two standard (Mark II) gauges for one month and was found to be only 1.04%. Evaporation losses from the project raingauges were similarly negligible at less than 0.6 mm/week (10 December 1997-23 March 1998). The precise location of all of the gauges used for above- and sub-canopy rainfall measurement was surveyed in closed-loop traverses using a Leica TC400 Total Station, a unit incorporating an electronic theodolite and laser-distance-measurement system. Such measurements, and the associated fixed gauge locations, were required for geostatistical modelling of spatial aspects of the rainfall data.

The initial assessment of the effect of forestry-related changes in canopy structure on $P_{\rm net}$ utilised data from all 345 sub-canopy gauges and 12 of the above-canopy gauges. A total of 80 sub-canopy gauges were located in two ‘plots’ of category ‘1’ canopy. Similarly category ‘2’ and ‘3’ canopy each had 80 gauges in two plots, while category ‘4’ forest was assessed with 85 gauges in two plots and category ‘5’ canopy 20 gauges in a single plot (Table 1). The raingauge plots, each approximately 300 m^2, were located only in forest patches very clearly falling within one of the canopy categories. Within the plots, the gauges were located randomly, giving a ‘stratified random design’ for the whole network of sub-canopy gauges. The above-canopy rainfall to be associated with that beneath the canopy of each plot was measured with three to eight gauges located in a nearby clearing. These ‘clearings’ were mostly haulage roads, skid trials and log-landings, which had a minimum diameter of 10–40 m and also 10–40 m away from the plots. All storage gauges were monitored on a variable frequency from an individual storm basis to once every two weeks.

Table 1. Sub-canopy rainfall (and associated gross rainfall) statistics measured beneath five canopy types produced by selective logging of lowland dipterocarp forest in the Ulu Segama Forest Reserve (Sabah) during the approximately 6-month period from 1 May to 27 November 1997.

Canopy category[a]	1	2	3	4	5
Gross rainfall (P_g)					
N^o P_g gauges	3	3	6	8	2
P_g total[b] (mm)	895.0	902.3	903.9	921.9	902.0
σ[c] (mm)	32.6	21.8	30.5	52.4	5.6
CV[d] (%)	4	2	3	6	1
95% confidence interval (mm) 37.6	25.1	24.9	37.0	7.9	
Difference in P_g variance[e]	–	ns[f]	ns	ns	$p < 0.10$
Difference in P_g mean[g]	–	ns	ns	ns	ns
Net rainfall (P_{net})					
N^o P_{net} gauges	80	80	80	85	20
P_{net} total[h] (mm)	815.0	758.7	719.2	795.5	771.6
σ(mm)	118.4	185.2	195.8	143.5	234.3
CV (%)	15	24	27	18	30
95 % confidence interval (mm)	25.9	40.6	42.9	30.5	102.7
Difference in P_{net} variance[i]	–	$p < 0.05$	$p < 0.01$	ns	$p < 0.01$
Difference in P_{net} mean[j]	–	$p < 0.05$	$p < 0.001$	ns	ns
Comparison of gross and net rainfall					
Difference in mean (P_g vs P_{net})[k]	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.05$
$P_g - P_{net}$ (mm)	80	144	185	126	130
95% confidence interval (mm)[l]	45.1	47.5	49.4	47.4	103.0
Difference in $P_g - P_{net}$ mean[m]	–	$p < 0.10$	$p < 0.01$	ns	ns
$\%P^{n}_{net}$ (%)	91.1 ± 6.7	84.1 ± 6.9	$79.6. \pm 6.9$	86.3 ± 6.8	85.6 ± 12.1

[a] 1 = undisturbed forest canopy; 2 = moderately impacted forest canopy; 3 = very disturbed and climber-covered canopy; 4 = cleared areas now with *Macaranga* spp. trees; 5 = cleared now with shrubs/herbs/sprawlers; canopy category 6 (no canopy) not shown.
[b] Only raingauges close to the P_{net} plots used within this analysis.
[c] Standard deviation.
[d] Coefficient of variation (or standard deviation normalised by the mean expressed as percent).
[e] Level of significance of difference in variance of P_g measured 'above' category 1 canopy and P_g measured 'above' the other canopies.
[f] Not significant, even at $p < 0.100$ level.
[g] Level of significance of difference in mean of P_g measured 'above' category 1 canopy and P_g measured 'above' the other canopies.
[h] Net preciptation figures exclude the estimated 1 percent stemflow.
[i] Level of significance of difference in variance of P_{net} measured beneath category 1 canopy and P_{net} measured beneath the other canopies.
[j] Level of significance of difference in mean of P_{net} measured beneath category 1 canopy and P_{net} measured beneath the other canopies.
[k] Based on standard errors for both P_g and P_net added in quadrature (Taylor 1982).
[l] Level of significance (2α) of difference in means of P_g and P_{net} measured at each canopy type.
[m] Level of significance of difference in mean of $P_g - P_{net}$ measured at category 1 canopy and $P_g - P_{net}$ measured at the other canopies. (NB. The *T-test* takes account of uncertainty in both P_g and P_{net}).
[n] Percent of the local P_g that is received beneath the canopy. (NB. $\%P_{net}$ is a quotient, so the fractional uncertainties in both P_g and P_{net} are added directly (Taylor 1982).

(A) Temporal structure of above-canopy rainfall

The temporal structure of the rainfall delivered to the canopy is the most significant control on the quantity of water delivered beneath the canopy (Lloyd 1990). This temporal structure might include (i) a diurnal distribution, (ii) an annual seasonality related to phenomena such as large scale reversals of the wind regime, (iii) inter-annual cycles related to phenomena such as the El Niño-Southern Oscillation (ENSO), (iv) any 'longer-term' drift in rainfalls and (v) rainstorm frequency and duration.

The diurnal distribution of above-canopy rainfall was examined by simple graphical and statistical summary of hourly and four-hourly data collected over a three year period (1995–1997) at the 'km63' raingauge in the DVFC locality. In contrast, identification of longer-term, temporal structures (i.e., annual and inter-annual cycles, and drift) within the DVFC daily records were analysed using Data-Based-Mechanistic (DBM) modelling. To aid interpretation, these techniques were also applied to the daily records for the nearest two MMS rainfall stations to DVFC, i.e., Lahad Datu and Tawau airports. The specific DBM modelling tool used in this instance is the Dynamic Harmonic Regression (DHR) model, which is a recursive interpolation, extrapolation and smoothing algorithm for non-stationary time-series (Young 1998; Young et al. 1999). The DHR model identifies three components in the time-series, i.e.,

$$P_{g(t)} = T_t + S_t + e_t, \qquad (1)$$

where $P_{g(t)}$ is the observed (above-canopy) rainfall time-series, T_t is the trend which includes the drift in long-term average rainfall and the inter-annual cycles, S_t is the periodic component related to annual and intra-annual seasonality, and e_t is the white noise. The S_t term is further defined as:

$$S_t = \sum_{i=1}^{R} \{a_{it} \cos(\omega_i t) b_{it} \sin(\omega_i t)\}, \qquad (2)$$

where $a_{i,t}$ and $b_{i,t}$ are the Time-Variable-Parameters (TVPs) of the model, R is the number of seasonal components, and ω_i are the set of frequencies chosen by reference to the spectral properties of the time-series. Optimisation of the TVPs was achieved by first estimating the Noise-Variance- Ratio (NVR) of the TVPs. This is achieved in the frequency domain by fitting the logarithmic pseudo-spectrum of the DHR model to the estimated logarithmic AutoRegressive (AR) spectrum of the observed rainfall series. The order of the AR model is identified via the Akaike Information Criterion. Once NVR parameters are optimised, a single run of two recursive algorithms, the Kalman Filter and Fixed-Interval-Smoothing equations provide estimates of the various components. The estimated trend component is further split into a very slowly changing drift and the inter-annual cyclic component. Since no assumptions are made as to the periodicity of the cycle, it is unlikely that any artefacts are introduced in the procedure. More detailed discussion of the DHR recursive techniques can be found within Young (1998) and Young et al. (1999). All analyses of the hourly and daily time-series were performed in the Matlab® programming environment. Simulation results of rainstorm frequency and duration in the DVFC and Eastern Sabah regions will be presented within Discenza et al. (in preparation).

Results

Plotting the four-hourly rainfall for the three year 'km63' record (Figure 3a) as a grouped histogram shows that there is a tendency for greater rainfall totals within the afternoon. The presence of extreme events within each of the four-hour time-series do, however, obfuscate clear diurnal patterns within the grouped histogram. To overcome this, rainfall occurring within the first hour of every day is totalled, the procedure is then repeated for all 24-h periods, and finally plotted. The resultant diagram (Figure 3b) clearly shows a strong diurnal modulation, with 43% of rainfall occurring between 2:00 to 4:00 p.m. Afternoon rains also characterised the diurnal rainfall distribution monitored about 40 km to the east of DVFC on the summit of Mount Silam during a 38-day sampling period in 1987 (Bruijnzeel et al. 1993). An afternoon peak in rainfall is similarly observed within some other tropical rainforests, for example, at Bukit Tarek, 50 km from the West coast of Peninsular Malaysia (Noguchi et al. 1996) and Reserva Florestal Ducke in the central Amazon (Lloyd 1990). This single peak in the mid-late afternoon is consistent with an inland equatorial rainfall regime where rain clouds develop as a result of convectional heating during the day (Watts 1955; Ramage 1964). In regions where the effects of phenomena such as sea breezes or katabatic winds become significant, the diurnal distribution may have different single or multiple times of peak rainfall (Watts 1955; Ramage 1964; Houze et al. 1981).

Figures 4a–c show the spectral frequency of the gross rainfall monitored on a daily basis at the DVFC,

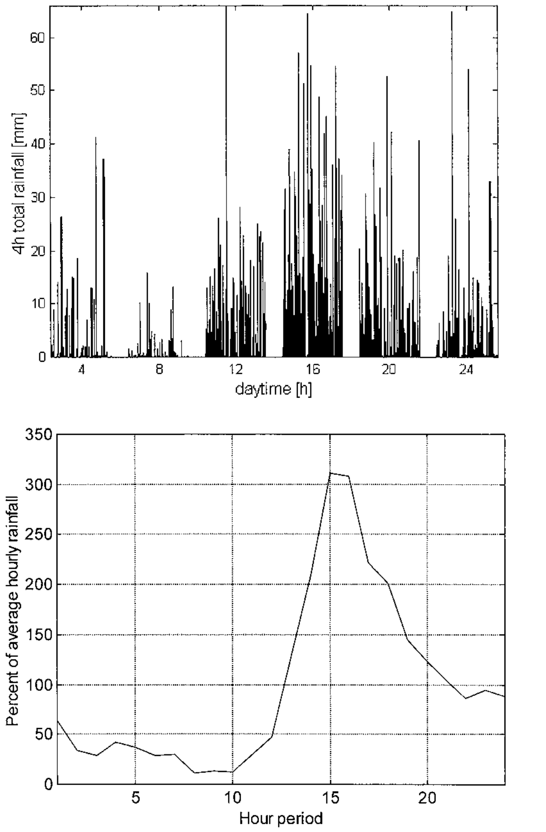

Figure 3. Diurnal distribution of rainfall monitored at the 'km63' tipping-bucket raingauge near to DVFC over a 3-year period shown as (a) a grouped histogram illustrating the time-series of rainfall in 4-hour diurnal periods, and (b) the percent of the average hourly rainfall.

Tawau and Lahad Datu meteorological stations. For simulation efficiency, the data are averaged over fortnightly periods. The records for Tawau (Figure 4b) show a pronounced spectral peak at 26-fortnightly periods and thereby indicates that there is a marked annual seasonality in rainfall at Tawau. The annual peaks in rainfall tend to occur during the late summer, though this unimodal pattern is disrupted during certain years (i.e., 1984–1985, 1988 and 1995; Figure 5b). Tawau records, therefore, show 'summer monsoon rains' also observable within the records of central Borneo (Kripalani & Kulkarni 1997, 1998). The data for DVFC (Figure 4a) have a annual peak (i.e., 26-fortnights), but it is neither (a) as large as at Tawau, nor (b) markedly larger than the peaks associated with its harmonics. This indicates that while some annual seasonality is present within the DVFC gross rainfall records, it is not as pronounced as that seen at Tawau. Furthermore, examination of a time-

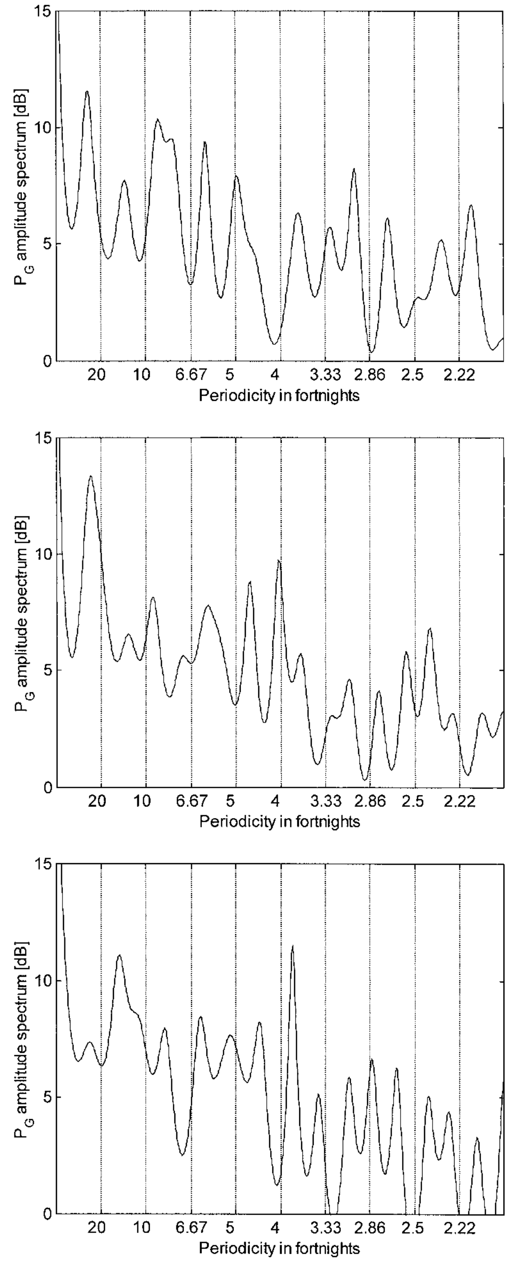

Figure 4. The spectral frequency of gross rainfall monitored at (a) DVFC, (b) Tawau, and (c) Lahad Datu in eastern Sabah.

series of the seasonal component (Figure 5a) indicates that the most stationary annual feature is a drier period in spring. Indeed, separate analysis of the monthly rainfall totals (1986–1998) supports this observation, with April having the smallest monthly total of only 120 mm (89 mm σ) or 54% of the monthly mean rainfall. The second most significant spectral peak within the DVFC records appears at 8.7-fortnights or every 4 months (Figure 4a). This peak relates to a relatively consistent increased rainfall during the three periods of (a) January–February, (b) July, and (c) October–November (Figure 5a). This weak intra-annual cycle is also just observable within the Lahad Datu records (Figure 5c), though it is the two drier periods that are the most marked (i.e., 12-fortnights spectral peak, Figure 4c) and they are of similar intensity (i.e., no marked spectral peak at 26-fortnights). The phenomena leading to the marked 'summer monsoon rains' at Tawau are, therefore, not as pronounced 81–89 km to the North (at DVFC or Lahad Datu). Adding further to the spatial inhomogeneity at the regional scale, the Lahad Datu and Tawau records exhibit a relatively pronounced peak at about 4-fortnightly periods (Figures 4b and 4c). Such a periodicity coincides with the 30–60-day oscillations in the eastward migration of the circulation cell over the tropics (Madden & Julian 1972; Weickmann et al. 1985). This cycle is not clearly observable within the DVFC records. All these spectral analyses clearly demonstrate the dangers of spatial interpolation of intra- annual rainfall over a meso-scale (i.e., 1000–10 000 km^2) tropical region where rainfall stations are tens of kilometres apart and convective cells are important. Spatial inhomogeneity in the temporal pattern within the 'eastern Sabah' region relate, at least in part, to the effects of land-sea interaction in coastal regions (Johnson & Priegnitz, 1981) and the interactions of different large-scale airflows (e.g., equatorial easterlies, trades and equatorial westerlies) in central and eastern Sabah (Wood 1948; Thompson 1951; Kripalani & Kulkarni 1998).

Figure 6 shows the dominant inter-annual cycles identified by the DHR model in the 11–17-year DVFC, Tawau and Lahad Datu data-series. These cycles have amplitudes of 2-4 mm d^{-1} against the mean daily rainfalls of about 6 mm d^{-1}. Dry periods centred on 1986–1987, 1992 and 1997 are observed within all three data-series. The longer records for Tawau and Lahad Datu also exhibit a drought in 1982-1983. These troughs in the inter-annual rainfall cycles have a periodicity in the 1980s and 1990s of 4.5–5.5 years and coincide with shifts in the El Niño-Southern Oscillation (Wolter & Timlin 1998). While each station experiences these dry periods, intra-regional variations in the intensity and timing are apparent. For example, the 1986–1987 dry spell is much less intense at Tawau than at the other two stations. Similarly, variation in the drought timing can be seen by closer examination of the same drought which is most intense at Tawau in July 1986, at DVFC in December 1986

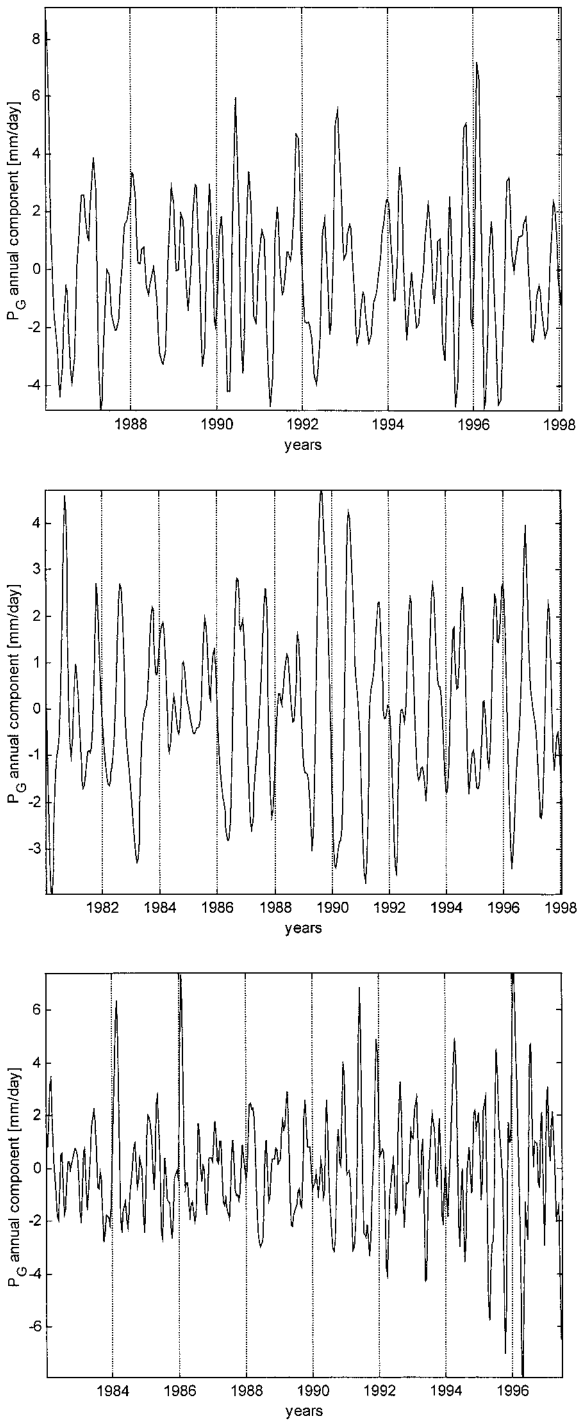

Figure 5. The time-series of the seasonal component (annual and intra-annual) of the rainfall distribution modelled from data collected at (a) the DVFC, (b) the Tawau, and (c) the Lahad Datu meteorological stations.

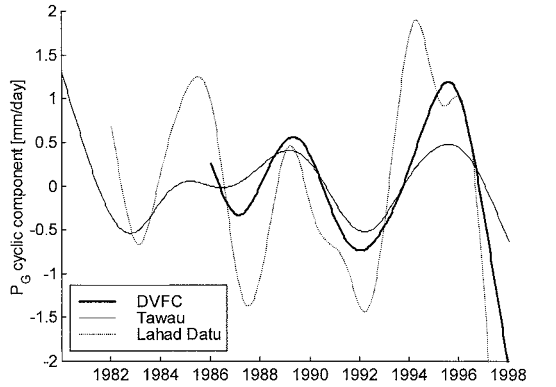

Figure 6. The time-series of the inter-annual cycles in rainfall modelled from data collected at the DVFC, Tawau and Lahad Datu meteorological stations.

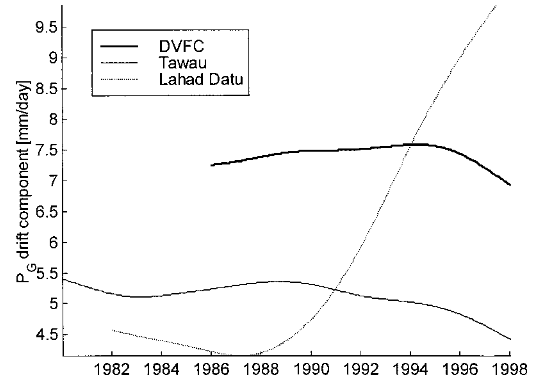

Figure 7. The time-series of 'longer-term' drift in the rainfall modelled from daily data collected at the DVFC, Tawau, and Lahad Datu meteorological stations.

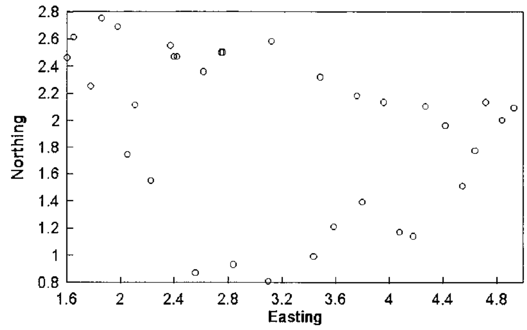

Figure 8. The spatial distribution of the raingauges monitoring gross-precipitation within the 10 km^2 study region near to DVFC. Axes are in kilometres horizontal distance.

and at Lahad Datu in June 1987. Again, the differences in time- series of raingauges a few tens of kilometres apart demonstrate the risks of interpolating temporal phenomena over meso-scale tropical regions.

The presence of drift in the rainfall totals over the 11–17 years of records was identified by the DHR modelling. While such 'longer-term' trends were not observed within the DVFC and Tawau rainfall records, over the period 1989–1997 Lahad Datu received a significant addition of rainfall of 6 mm d^{-1} (Figure 7). High convectional instability in equatorial regions means that the local development of cumulus clouds, and their associated rains, will be very sensitive to even small modifications to the local surface albedo, heat capacity or evapo-transpiration resulting from land-use changes (J.F.R. McIlveen, pers. comm.). As a consequence, the recent urbanisation and plantation development in the Lahad Datu area (Talip 1996) may be having an impact on the local rainfall. As this preliminary analysis only utilises relatively short (i.e., 11–17 year) records, it is, however, unrealistic to relate changes in the 'drift component' to impacts of local land-use change without further analysis, as longer-term cycles and trends within natural climatic phenomena are known to be present within the Borneo data-series (Walsh 1996). Indeed, Tych and Chappell (unpubl. data), again using the DHR model, have identified 18-year cycles within a 102-year rainfall record for Sandakan airport on the northern coast of Sabah. Further, Kripalani & Kulkarni (1997) describe 'epochs' of above- and below-average rainfall within time-series for Southeast Asia which exhibit a periodicity ranging from 10 to 30 years. Possibly, the 'epochs' for Lahad Datu, Tawau and DVFC are (a) out-of- phase, (b) have different intensities, or (c) have different durations.

The DVFC time-series analysis clearly identifies the importance of temporal variations in above-canopy rainfall caused by the presence of mid-late afternoon convective storms and ENSO phenomena in particular. Future analyses of the spatial variations in net precipitation (and wet-canopy-evaporation), therefore, ought to consider spatial patterns during individual convective storms and ENSO droughts.

(B) Spatial structure of above-canopy rainfall

The complex spatial patterns of sub-canopy rainfall will be dependent on the spatial patterns of (a) the rainfall received by the forest canopy and (b) the canopy properties. As the spatial characteristics of the P_g are expected to be less complex than those beneath the canopy, geostatistical (or stochastic) analysis of the P_g is, therefore, a first step in understanding the spatial structure of sub-canopy rainfall (Moliŏvá & Hubert 1994). Within this analysis, P_g data from 34 of the 50 storage gauges within the 10 km^2 DVFC study area (Figure 8) were examined using geostatistical modelling. The relationship between the raingauge catch and horizontal distance between raingauges was analysed by constructing 'experimental semi-variograms', where an estimate of the semi-variance $\hat{\lambda}(h)$ at lag distance (h) is:

$$\hat{\gamma}(h) = \frac{1}{2(n-h)} \sum_{i=1}^{n-h} \{z(i) + z(i+h)\}^2 , \qquad (3)$$

where z is the point rainfall total and n is the sample position (Journel & Huijbregts 1978). The parameters of the most appropriate model structure describing the relationship between the semi-variance in raingauge totals and lag distance were then identified. This analysis was performed on rainfall totals recorded over the 6-month period from 6 May to 27 November 1997 and for a single late afternoon event.

Results

The 34 raingauge totals for the 6-month period have a spatial mean of 1009.1 mm, a variance of 8633.0 mm^2 and a spatial coefficient of variation (CV) of 9.2%, while the data for the single event that occurred on the 17 September 1997 had a 14.7 mm mean, 66.7 mm^2 variance, and 55% CV. The clear reduction in the spatial CV from one to N-events is expected, as the patchiness of individual, local convective events will be smoothed by integration with other equally patchy events in the time-series. At the 10 km^2 scale, the 9.2% CV remaining after this integration process may be caused by the presence of local topographic (i.e., altitudinal, aspect or slope) effects on rainfall. Such topographic analysis is ongoing (Bidin in preparation).

The 'experimental variography' undertaken shows a monotonically increasing semi-variance with lag distance. This indicates that as the distance between the raingauges increases, the rainfall totals recorded by pairs of gauges become more dissimilar. This phenomenon is exhibited within the data averaged over 6-months (Figure 9a) and within the data specific to the individual convective storm of the 17 September 1997 (Figure 9b). Local convective rain cells beneath individual cumulus clouds are typically 1–10 km in diameter (Barry & Chorley 1982). As the experimental variogram for the single event does not exhibit a 'sill' towards the largest observed lag distances (ca. 3 km), this indicates that the 10 km^2 area contained either

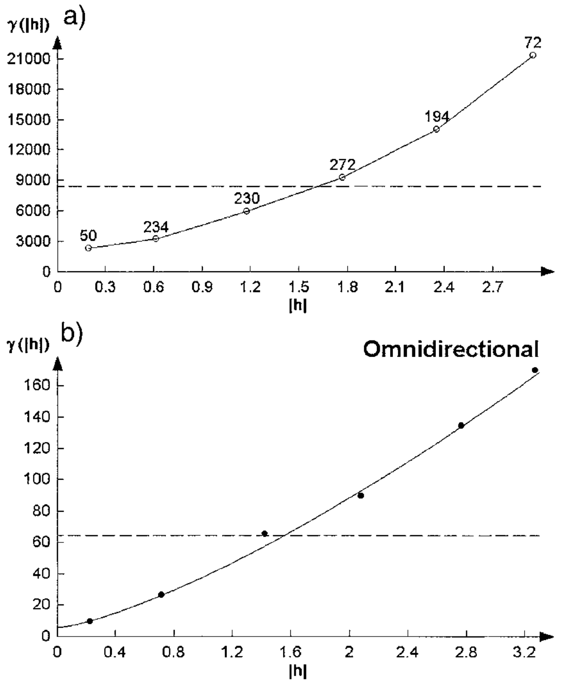

Figure 9. 'Experimental variograms' characterising the spatial variability in gross-precipitation within the 10 km^2 study region near to DVFC for (a) the 6-month period from 6 May to 27 November 1997, and (b) a single 15 mm convective event on the 17 September 1997. The number of raingauges pairs used to derive each value in (a) are shown, while the Power Variogram Model (solid line) fitted to the 'experimental variogram' for the single event is shown in (b). The lag spacing (h) has the units of kilometres, while the estimate of the semi-variance $(\hat{\lambda}(h))$ has the units of mm^2.

(a) a larger convective cell, (b) a group of small convective rain cells, or (c) a moving small cell. Clearly, at the scale of the 5000 km^2 'eastern Sabah' region, maximum lag distances would exceed the size of individual convective cells and be comparable to that of cell clusters called 'mesoscale convective systems' (Houze et al. 1981). A 'sill' in the variogram (where the maximum extent of spatial correlation has been exceeded) might, therefore, be observable if intensive spatial sampling were to be undertaken at this larger scale. Indeed, other recent studies examining the spatial structure of rainfall in areas where convective cells are important exhibit variogram sills only after 10–40 km lag distances (Borga & Vizzaccaro 1997; Lebel & Le Barbé 1997).

As the rate of change of dissimilarity in raingauge totals in the DVFC area increases with increasing distance and a 'sill' is not reached within the experimental variogram, a (theoretical) Power Variogram Model (PVM) best describes the change in the semi-variance:

$$\gamma(h) = wh^{\alpha}, \quad (4)$$

where w is the positive variance contribution (or scaling term) and α is the power exponent of between 0 and 2. The PVM for the 17 September 1997 event has an exponent of approximately 1.3 (i.e., a concave-upward power relation) and a scaling term of about 35 (Figure 9b). A 'nugget variance' (c_0) of 6 has been added to the PVM as the experimental variogram appears to cross the y-ordinate slightly above zero. Such a small nugget variance (i.e., 9% of total variance) does, however, indicate both the similarity of totals where gauges are only metres apart and little error within the raingauge measurements themselves (Goodrich et al. 1995). In some contrast, the power exponent of a PVM fitted to the 6-month data approaches 2 and may, therefore, indicate that 'deterministic drift' is present within the experimental variogram (Pannatier 1996). Such drift might be caused by local altitudinal enhancement of convection (Goodrich et al. 1995) or upwind/downwind effects of local topography (Lyons & Bonell 1992). An *a priori* parameterisation of these effects would lead to more robust spatial models. The preliminary geostatistical analysis does, however, indicate that as the variography lacks both large 'nugget' and 'hole' effects it is useful in identifying spatial structures in above-canopy rainfall over a 10 km^2 area of rainforest. These spatial models will allow kriging techniques (Journel & Huijbregts 1978) to be used to interpolate rainfall fields accurately from the sparse raingauge networks of other research programmes. These improvements are required for further developments in the modelling of rainfall-runoff and rainfall-sediment behaviour within 'experimental catchments' (Chappell et al. 1998, 1999a). Furthermore, identification of models that define the stochastic and topography-related patterns in above-canopy rainfall are important to the separation of the independent controls on P_{net} of (a) the above-canopy rainfall, and (b) the canopy structure.

(C) Canopy structure and sub-canopy rainfall

Summary data for the period 1 May to 27 November 1997 (211 days) were used to examine the relationship between sub-canopy rainfall and each of the 'types' of canopy left by selective logging of lowland dipterocarp forest (Table 1). Throughfall (i.e., P_{ld} + P_{dt} in Figure 1) within each vegetation category was calculated as a proportion of the local above-canopy precipitation. The remaining component of the sub-canopy rainfall, stemflow, which only amounted to approximately 1% of the above-canopy rainfall (Bidin in preparation) is not examined in detail within this preliminary analysis,

Results

Over the 6-month monitoring period, the 80 raingauges beneath the undisturbed patches of rain forest collected 91.1% of that monitored within nearby canopy gaps (Table 1). Assuming stemflow is 1% of the above-canopy rainfall, the resultant 8% of wet-canopy-evaporation (E_{wc}) equates to an annual depth of 113 mm during the ENSO drought year (i.e., $65.2 \times 365/211$). While this rate of E_{wc} from virgin forest is relatively low compared to many other published rates for undisturbed lowland dipterocarp forests in Southeast Asia (Table 2), similarly low rates can be found in the literature. For example, a rate of 8% E_{wc} has been observed in the undisturbed lowland dipterocarp forest at Pasoh, West Malaysia (UNESCO 1978), and Lloyd et al. (1988) has reported a figure of 9% E_{wc} for undisturbed Amazonian terra firma rain forest. Furthermore, Asdak et al. (1998) has noted a large variability in E_{wc} from different undisturbed tropical rain forests and suggested that more studies, particularly those incorporating intensive sampling strategies, are required to understand such variations within the tropics. Recently published results from Southeast Asia (Table 2) do, however, appear to exhibit a trend. There is a strong and significant positive linear relationship between the annual totals of above-canopy rainfall ($P_{g(yr)}$) and the annual percentage of wet-canopy-evaporation ($\%E_{wc(yr)}$), where:

$$\%E_{wc(yr)} = 0.0088 P_{g(yr)} - 7.5535 \quad (r^2 = 0.91,\ p < 0.05). \quad (5)$$

In other words, the proportion of the rainfall lost to wet-canopy-evaporation increases with increasing annual rainfall. The lower proportion of the E_{wc} for virgin forest at DVFC observed in 1997 compared to that observed in 1989–1990 at a nearby site (Sinun et al. 1992) may be, therefore, associated with the reduced total of gross rainfall recorded during the intense 1997–1998 El Niño year. Such an apparent correlation between E_{wc}-proportion and total P_g probably results from changes in storm frequency through ENSO cycles (W. T. Swank, pers. comm.).

Rainfall beneath disturbed forest patches within the study area was monitored over the same 6-month

Table 2. Recent studies presenting annual rates of wet-canopy-evaporation (E_{wc}) measured in undisturbed lowland dipterocarp forest of Southeast Asia.

Reference	Location	No. gauges (sub-canopy)	Annual		
			Rainfall (mm)	E_{wc} (mm)	E_{wc} (%)
This study	East Sabah	80	1549[a]	113	8
Asdak et al. 1998	Central Kalimantan	50	2199	251	11
Kasran 1989	West Malaysia (central)	4[b]	3722	1005	27
Sinun et al. 1992	East Sabah[c]	40	2824	569	17
Yusop 1996	West Malaysia (central)	4	2723	354	13

[a]Extrapolated from a 211 day total of 895.5 mm.
[b]0.76 m long troughs, rather than raingauges.
[c]Only 5 km from the site used within this study.

period as within the virgin forest patches. First, Table 1 shows that the wet-canopy evaporation (i.e, $P_g - P_{\text{net}}$) from *Macaranga* spp. trees (category 4 cover) and the shrubs/herbs (category 5 cover) was not statistically different ($p < 0.100$) to that penetrating the virgin forest.

Secondly, the data from the 160 gauges located beneath category 2 and 3 vegetation – the moderately and severely impacted patches of tree canopy are significantly different to those from the undisturbed forest. Throughfall beneath the two disturbed forest categories amounted to 84.1% and 79.6% of received rainfall, respectively (Table 1). These are statistically significant reductions in the quantity of rainfall penetrating the disturbed canopies relative to the situation within virgin forest. Again assuming for this preliminary analysis a stemflow of 1% of above-canopy rainfall, this gives apparent rates of wet-canopy-evaporation of 15% and 19%, respectively. There are three preliminary explanations for the apparent increases in E_{wc} following canopy disturbance. First, there is an increased density of leaves on the outer surfaces of the disturbed canopy resulting from the expansion of the woody climbers. This outer surface experiences the highest temperatures and rates of net radiation and, therefore, the potential for high rates of wet-canopy-evaporation. Thus, increasing leaf density in this part of the canopy may have a disproportionate effect on the whole-forest E_{wc}. Second, selective removal of upper canopy trees during silvicultural operations, increases the roughness of the forest surface, which in turn increases the levels of turbulence over the canopy. As increasing atmospheric turbulence over the canopy (i.e., the 'atmospheric conductance' term, Dingman 1994) increases evaporation, then rates of E_{wc} are likely to increase. The third explanation is related to the interaction between the canopy surface and the above- canopy rainfall. Turbulent eddies in the wind above the forest canopy will mean that rainfall often approaches the forest canopy at an acute angle. This may mean that patches of high virgin forest 'intercept' more rainfall at the canopy surface than lower patches of disturbed canopy. In other words, the higher canopies of virgin forest may shelter the lower disturbed canopies (cf., Barry & Chorley 1982, p. 300).

Conclusions and implications

Ten conclusions can be derived from the analysis of the gross rainfall and canopy controls on net precipitation within the studied rainforest.

(1) Forty-three percent of the above-canopy rainfall received by the Ulu Segama rain forest is observed in the mid-afternoon (2–4 p.m.). A similar proportion of the sub-canopy or net rainfall is, therefore, expected between these two hours. A single afternoon or early evening peak in rainfall is indicative of a system dominated by local convective cells (cumulus clouds) and as a result, one that is expected to give a highly heterogeneous spatial rainfall pattern. Clearly, such a situation would demand both a relatively high density of raingauges and an understanding of the spatial structure of the rainfall for estimates of both (a) spatially-averaged rainfall over a typical 'experimental catchment', and (b) rainfall received by 'research plots' distributed throughout at region of a

few square kilometres. The extent of seasonal variations in the diurnal rainfall distribution is currently under investigation (Bidin in preparation).

(2) The dominance of mid-afternoon rains combined with the qualitative observation that the canopies wetted by these rains stay wet until the next day, may have local meteorological implications. First, during calm nights, such canopy water would probably enhance the formation of 'radiation fog' within and just above the upper canopy (Watts 1955; J. F. R. McIlveen, pers. comm.). Second, it may also mean that some water stored on the canopy surfaces is not evaporated from wet surfaces until after perhaps as many as 20 hours (i.e., 3 p.m. to 10 a.m.). The diurnal distribution in wet-canopy-evaporation may, therefore, significantly lag behind that of the above- and sub-canopy rainfall.

(3) Very little annual seasonality is apparent within the daily rainfall records at DVFC. Twelve-month sampling periods of net precipitation (or wet-canopy-evaporation), required in areas with a marked annual seasonality, therefore, may not be necessary for hydrometeorological work in the Ulu Segama region of Sabah. As annual cycles in the rainfall are apparent within the Tawau records, this means that net precipitation or wet-canopy-evaporation studies undertaken in areas only 80 km to the south southeast of DVFC would need at least annual time-series. This also highlights the risks in extrapolation or interpolation of rainfall totals throughout sparsely instrumented tropical regions as small as 5000 km^2.

(4) The presence of marked droughts with a recurrence interval of 4.5 to 5.5 years within the rainfall series for eastern Sabah, that coincide with the periodicity of El Niño-Southern Oscillation (ENSO) phenomena, mean that any short-term studies on for example the soil-moisture-status of rain forest soils, the rates of erosion in rain forest terrain or the associated status of the aquatic biology, should be replicated within both drought and non-drought periods.

(5) The preliminary geostatistical analysis indicates that a deterministic spatial structure may be affecting the experimental variogram for the 10 km^2 study region near DVFC. This structure may be related to local altitudinal enhancement of convection or upwind/downwind effects of local topography. Future analysis needs to identify and then de-trend these effects prior to further variography. The lack of a 'sill', large 'nugget' or 'hole' effects within the variogram for a rain forest region the size of the 0.5–10 km^2 experimental catchment does, however, indicate that the spatial patterns of above-canopy rainfall can be modelled geostatistically. This means that the spatial structure of above-canopy rainfall can be separated from the more complex sub-canopy patterns to be examined within the future analysis of Bidin (in preparation).

(6) Comparison of the proportion of the gross rainfall lost as wet-canopy evaporation for patches of undisturbed lowland dipterocarp forest near DVFC with those from recent studies undertaken within Southeast Asia indicates that differences may relate to changes in annual rainfall totals. As the data-set for this comparison is small, such a conclusion is tentative and requires further investigation. A rate of 8 percent wet- canopy evaporation for the undisturbed lowland dipterocarp forest near DVFC is low, but is not inconsistent with some published studies (e.g., UNESCO, 1978) and with rates observed by ongoing studies elsewhere in the tropics (L. A. Bruijnzeel, pers. comm.).

(7) Within the Ulu Segama forest, the moderately impacted and creeper-covered, highly damaged patches of forest have reduced rates net-precipitation and elevated levels of wet-canopy-evaporation in comparsion to the undisturbed patches. It should be noted that such changes relate to a period some 9 years post logging and during a severe ENSO-drought. The reduction in net-precipitation needs further investigation, but may relate to (a) elevated wet-canopy-evaporation from creeper-covered surfaces, (b) rougher forest surfaces, or (c) the lower canopies of disturbed forest patches receiving less rainfall due to local sheltering effects. The large differences in net-precipitation between the patches of (i) undisturbed and *Macaranga* spp. forest, and (ii) the moderately impacted cum creeper-covered forest patches, will mean that the hectare-scale spatial variability in sub-canopy rainfall will have increased in comparison to large regions of undisturbed forest. This will mean that spatial patterns of infiltation-excess overland flow and litter moisture status will be more heterogeneous on natural slopes within selectively-logged forest and, therefore, more difficult to predict. Analysis to identify which of these explanations is the most robust, is ongoing (Bidin in preparation).

Rates of transpiration might be increased or decreased by selective logging and would, therefore, either magnify or offset changes in the water-yield of a catchment resulting from changes in wet-canopy-evaporation. The 10 km^2 region near DVFC where net-precipitation has been studied, contains the 0.44 km^2 'Baru Experimental Catchment' (Chappell et al. 1998, 1999a). Bidin (in preparation) is currently undertaking the water-balance for this catchment, to assess the net result of separate changes in wet-canopy-evaporation and biological transpiration. Estimation of the catchment-average net precipitation will be undertaken by integrating the average rates per canopy category, multiplying these values by the proportion of the catchment covered by that category and then summing the products. Areal photographs, taken from 30 to 600 m above the canopy, will be used aid in the estimation of the proportion of the Baru Experimental Catchment covered by each canopy category. Despite this, uncertainties in the catchment-average net precipitation will result from uncertainties in the classification of all patches of canopy into one of the 6 discrete categories defined (Bellehumeur et al. 1997).

Acknowledgements

The authors would like to thank Rahman Merami (UMS-supported assistant) for help in the collection of the gross and net precipitation data in the DVFC locality, Johnny Larenus and Mohd. Jamal Hanapi (DVFC Hydrology Project) for the collection of the DVFC meteorological station and 'km63' data, and the Malaysian Meteorological Service for the rainfall data from the Lahad Datu and Tawau meteorological stations. Ismail Abd. bin Samat and Shaidih Abd. bin Samat (Royal Society Survey Team) are thanked for their detailed electronic survey. The comments of Dr J. F. Robin McIlveen (Lancaster University, UK), Prof Wayne T Swank (Coweeta Hydrologic Laboratory, USA), Dr L. A. (Sampurno) Bruijnzeel (Free University, Netherlands) and reviewers of the manuscript are much appreciated. M.D. Sherlock is thanked for the basemap for Figure 2. The support of Prof. Dr Noh Dalimin (Universiti Malaysia Sabah), Dr. Waidi Sinun of the Forestry Division (Innoprise Corporation) of Yayasan Sabah, and the Danum Valley Management Committee are gratefully acknowledged. Financial support for this work has been provided by Universiti Malaysia Sabah (UMS), UK Natural Environment Research Council (grant GR3/9439) and the South East Asia Rain forest Research Programme of the Royal Society of London (publication number A/306).

References

Asdak, C. Jarvis, P. G., van Gardingen, P. & Fraser, A. 1998. Rainfall interception loss in unlogged and logged forest areas of Central Kalimantan, Indonesia. J. Hydrol. 206: 237–244.

Barry, R. G. & Chorley, R. J. 1982. Atmosphere, weather and climate. Fourth Edition. Methuen, London.

Bellehumeur, C., Legendre, P. & Marcotte, D. 1997. Variance and spatial scales in tropical rain forest: Changing the size of sampling units. Plant Ecol. 130: 89–98.

Bidin, K. in preparation. Spatial and temporal structure of gross and net precipitation within a selectively-logged forest catchment. Unpublished Ph.D. thesis, University of Lancaster, Lancaster.

Borga, M. & Vizzaccaro, A. 1997. On the interpolation of hydrologic variables: formal equivalence of multiquadratic surface fitting and kriging. J. Hydrol. 195: 160–171.

Brooks, S. M. & Spencer, T. 1995. Vegetation modification of rainfall characteristics: implications for rainfall erosivity following logging in Sabah, Malaysia. J. Trop. For. Sci. 7: 435–446.

Bruijnzeel, L. A., Waterloo, M. J., Proctor, J., Kuiters, A. T. & Kotterink, B. 1993. Hydrological observations in montane rain forests on Gunung Silam, Sabah, Malaysia, with special reference to the *'Massenerhebung'* effect. J. Ecol. 81: 145–167.

Calder, I. R. 2001 Canopy processes: implications for transpiration, interception and splash induced erosion, ultimately for forest management and water resources. Plant Ecol. 153: 203–214 (this volume).

Chappell, N. A., Franks, S. W. & Larenus, J. 1998. Multi-scale permeability estimation for a tropical catchment. Hydrol. Process. 12: 1507–1523.

Chappell, N. A., McKenna, P., Bidin, K, Douglas, I, & Walsh, R. P. D. 1999a. Parsimonious modelling of water and suspended-sediment flux from nested-catchments affected by selective tropical forestry. Philos. Trans. R. Soc. Lond. Ser. B 354: 1831–1846.

Chappell, N. A., Ternan, J. L. & Bidin, K. 1999b. Correlation of physicochemical properties and sub-erosional landforms with aggregate stability variations in a tropical Ultisol disturbed by forestry operations. Soil Tillage Res. 50: 55–71.

Conway, S. 1982. Logging practices. Miller Freeman Publications, San Francisco.

Dingman, S. L. 1994. Physical hydrology. Prentice Hall, Englewood Cliffs.

Discenza, A. R., Whittaker, J., & Chappell, N. A., in preparation. Stochastic modelling of tropical rainfall occurrence processes at daily and hourly time-scales.

Douglas, I., Bidin, K., Balamurgam, G., Chappell, N. A., Walsh, R. P. D., Greer, T. & Sinun, W. 1992. The role of extreme events in the impacts of selective tropical forestry on erosion during harvesting and recovery phases at Danum Valley, Sabah. Philos. Trans. R. Soc. Lond. Ser. B 354: 1749–1761.

Douglas, I., Spencer, T., Greer, T., Bidin, K., Sinun, W. & Wong, W. M., 1992. The impact of selective commercial logging on stream hydrology, chemistry and sediment loads in the Ulu Segama Rain Forest, Sabah. . Philos. Trans. R. Soc. Lond. Ser. B 335: 397–406.

Eschenbach, C., Glauner, R., Klein, M. and Kappen, I. 1998. Photosynthesis rates of selected tree species in lowland dipterocarp rain forest of Sabah, Malaysia. Trees-Struct. Funct. 12: 356–365.

Goodrich, D. C., Faurès, J-M., Woolhiser, D. A., Lane, L. J. & Sorooshian, S. 1995. Measurement and analysis of small-scale convective storm rainfall variability. J. Hydrol. 173: 283–308.

Henderson-Sellers, A., Dickinson, R. E., Durbridge, T. B., Kennedy, P. J., McGuffe, K. & Pitman, A. J. 1993. Tropical deforestation:

modelling local to regional-scale climatic change. J. Geophys. Res. 98 (D4): 7289–7315.

Herwitz, S. R. 1985. Interception storage capacities of tropical rain forest trees. J. Hydrol. 77: 237–252.

Houze, R. A., Geotis, S. G., Marks, Jr., F. D. & West A. K. 1981. Winter monsoon convection in the vicinity of north Borneo. Part 1: structure and time variation of the clouds and precipitation. Mon. Weather Rev. 109: 1595–1614.

Johnson R. H. & Priegnitz, D. L. 1981. Winter monsoon convection in the vicinity of North Borneo. Part II. Effects on large-scale fields. Mon. Weather Rev. 109: 1619–1632.

Journel, A. G. & Huijbregts, C. J. 1978. Mining geostatistics. Academic Press, New York.

Kasran, B. 1989. Rainfall interception in dipterocarp forest of Penninsular Malaysia. Pp. 1–15. In: Regional seminar on tropical forest hydrology. Forest Research Institute of Malaysia, Kuala Lumpur.

Kripalani, R. H. & Kulkarni, A. 1997. Rainfall variability over South-east Asia – connections with Indian monsoon and ENSO extremes: new perspectives. Int. J. Clim. 17: 1155–1168.

Kripalani, R. H. & Kulkarni, A. 1998. The relationship between some large-scale atmospheric parameters and rainfall over Southeast Asia: a comparison with features in India. Theor. Appl. Clim. 59: 1–11.

Lebel, T. and Le Barbé, L. 1997. Rainfall monitoring during HAPEX-Sahel. 2. Point and areal estimation at the event and seasonal scales. J. Hydrol. 188: 97–122.

Lloyd, C. R. 1990. The temporal distribution of Amazonian rainfall and its implications for forest interception. Quart. J. Roy. Meteorol. Soc. 116: 1487–1494.

Lloyd, C. R. Gash, J. H. C., Shuttleworth, W. J. & Marques Filho, A de O. 1988. The measurement and modelling of rainfall interception by Amazonian rain forest. J. Hydrol. 43: 277–294.

Lyons, W. F. & Bonell, M. 1992. Daily mesoscale rainfall in the tropical wet/dry climate of the Townsville area, north-eastern Queensland during the 1988/89 wet season: synoptic scale airflow considerations. Int. J. Clim. 12: 655–684.

Madden, R. A. & Julian, P. R. 1972. Description of global scale circulation cells in the tropics with a 40-50 day period. J. Atmos. Sci. 29: 1109–1123.

Martin-Smith, K. 1999. Biodiversity patterns of tropical freshwater fish following selective timber extraction: a case study from Sabah, Malaysia. Ital. J. Zool. 65: 363–368.

Moliǒvá, H. & Hubert, P. 1994. Canopy influence on rainfall fields' microscale structure in tropical forests. J. Appl. Meteorol. 33: 1464–1467.

Newbery, D. McC., Campbell, E. J. F., Lee, Y. F., Ridsdale, C. E. & Still, M. J. 1992. Primary lowland dipterocarp forest at Danum Valley, Sabah, Malaysia: structure, relative abundance and family composition. Philos. Trans. R. Soc. Lond. Ser. B. 335: 341–356.

Newell, R. E. & Gould-Stewart, S. 1981. A stratospheric fountain ? J. Atmos. Sci. 12: 2789–2796.

Noguchi, S., Nik, A. R., Sammori, T., Tani, M., & Tsuboyama, Y. 1996. Rainfall characteristics of tropical rain forest and temperate forest: comparison between Bukit Tarek, Peninsular Malaysia and Hitachi Ohta in Japan. J. Trop. For. Sci. 9: 206–220.

Pannatier, Y. 1996. Variowin: software for spatial data analysis in 2D. Springer-Verlag, New York.

Pinard, M. A. & F. E. Putz. 1996. Retaining forest biomass by reducing logging damage. Biotropica 28: 278–295.

Ramage, C. S. 1964. Diurnal variation of summer rainfall of Malaya. J. Trop. Geogr. 19: 62–68.

Riehl, H. 1954. Tropical meteorology. McGraw-Hill, New York.

Sherlock, M. D., 1997. Plot-scale hydrometric and tracer characterisation of soil water flow in two tropical rain forest catchments in Southeast Asia. Unpublished PhD thesis, Lancaster University.

Shuttleworth, W. J. 1988. Evaporation from Amazonian rain forest. Proc. R. Soc. Ser. B 233: 321–346.

Sinun, W., Meng, W. W., Douglas, I. & Spencer, T. 1992. Throughfall, stemflow, overland flow and throughflow in the Ulu Segama rain forest, Sabah, Malaysia. Philos. Trans. R. Soc. Lond. Ser. B 233: 321–346.

Talip, M. A., 1996. Using a Geographical Information System (GIS) to analyse land use changes in eastern Sabah, Malaysia. Unpublished M.Sc. thesis, University of Manchester, UK.

Taylor, J. R. 1982. An introduction to error analysis. University Science Books, Mill Valley.

Thompson, B. W. 1951. An essay on the general circulation of the atmosphere over South-East Asia and the West Pacific. Quart. J. Roy. Meteorol. Soc. 77: 569–597.

UNESCO. 1978. Tropical forest ecosystems (Chapter 12). UNESCO, Paris.

Walsh, R. P. D. 1996. Drought frequency changes in Sabah and adjacent parts of northern Borneo since the late nineteenth century and possible implications for tropical rain forest dynamics. J. Trop. Ecol. 12: 385–407.

Watts, I. E. M. 1955. Equatorial weather: with particular reference to Southeast Asia. University of London Press, London.

Weickmann, K. M., Lussky, G. R. & Kutzbach, J. E. 1985. Intraseasonal (30–60 day) fluctuations of outgoing longwave radiation and 250 mb streamfuction during northern winter. Mon. Weather Rev. 111: 1838–1858.

Whitmore, T. C. 1998. An introduction to tropical rain forests. Second Edition. Oxford University Press, Oxford.

Wolter, K. & Timlin, M. S. 1998. Measuring the strength of ENSO - how does 1997/98 rank ? Weather 53: 315–324.

Wood, C. A. 1948. Report on the weather of the Borneo-Celebes region, 1946. Quart. J. Roy. Meteorol. Soc. 74: 144–160.

Young, P. C. 1998. Data-based mechanistic modelling of environmental, ecological, economic and engineering systems. Environ. Modell. Softw. 13: 105-122.

Young, P. C., Pedregal, D. J., & Tych, W. 1999. Dynamic harmonic regression. J. Forecasting 18: 369–394.

Yusop, Z. 1996. Nutrient cycling in secondary rain forest catchments of Peninsular Malaysia. Unpublished Ph.D. thesis, University of Manchester, Manchester.