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Characteristics of rain events at an inland locality in northeastern Borneo, Malaysia

Kawi Bidin[1] and Nick A. Chappell[2]*

[1] *School of Science and Technology, Universiti Malaysia Sabah, 88999 Kota Kinabalu, Malaysia*
[2] *Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK*

Abstract:

Understanding the intensity and duration of tropical rain events is critical to modelling the rate and timing of wet-canopy evaporation, the suppression of transpiration, the generation of infiltration-excess overland flow and hence to erosion, and to river responsiveness. Despite this central role, few studies have addressed the characteristics of equatorial rainstorms. This study analyses rainfall data for a 5 km^2 region largely comprising of the 4 km^2 Sapat Kalisun Experimental Catchment in the interior of northeastern Borneo at sampling frequencies from 1 min^{-1} to 1 day^{-1}.

The work clearly shows that most rainfall within this inland, forested area is received during regular short-duration events (<15 min) that have a relatively low intensity (i.e. less than two 0·2 mm rain-gauge tips in almost all 5 min periods). The rainfall appears localized, with significant losses in intergauge correlations being observable in minutes in the case of the typical mid-afternoon, convective events. This suggests that a dense rain-gauge network, sampled at a high temporal frequency, is required for accurate distributed rainfall-runoff modelling of such small catchments. Observed rain-event intensity is much less than the measured infiltration capacities, and thus supports the tenet of the dominance of quick subsurface responses in controlling river behaviour in this small equatorial catchment. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS diurnal; duration; intensity; rainfall; storm event; tropics

INTRODUCTION

There is a dearth of studies describing the short-term characteristics of rainfall within humid tropical environments (Manton and Bonell, 1993; Jackson and Weinand, 1994; Bonell *et al.*, 2004). Based on the few reports available, the characteristics of tropical rain-events are thought to regulate the rate of wet-canopy evaporation (Lloyd, 1990; Asdak *et al.*, 1998; Schellekens *et al.*, 1999; Chappell *et al.*, 2001), transpiration supression (Szarzynski and Anuf, 2001), shallow water-table fluctuations (Bidin *et al.*, 1993), and runoff behaviour (Robinson and Sivapalan, 1997; Bonell *et al.*, 2004). Many studies have also attributed the temporal variation in tropical geomorphic activity to rain-event characteristics, particularly those of large events (Douglas *et al.*, 1999; Morgan, 2004).

Within this study, the short-term (i.e. 1 min to 1 day) behaviour of rainfall is characterized for a small (5 km^2) equatorial region in the interior of northeastern Borneo. This area is the focus of a major ecological research programme (Marshall and Swaine, 1992; Newbery *et al.*, 2000), and the new work aims to complement recent modelling work on longer-term (e.g. interannual) variations in rainfall and associated ecological and hydrological processes within Borneo Island (Walsh, 1996; Douglas *et al.*, 1999; Chappell *et al.*, 2001, 2004b; Tangang, 2001).

Borneo is at the centre of the so-called Maritime Continent of Southeast Asia. This region is thought to exert a strong influence on global climate due to the very large input of evaporated water into the upper troposphere

* Correspondence to: Nick A. Chappell, Lancaster Environment Centre, Lancaster LA1 4YQ, UK. E-mail: n.chappell@lancaster.ac.uk

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(Newell and Gould-Stewart, 1981; Chen and Houze, 1997; Neale and Slingo, 2003; Fueglistaler *et al*., 2004) and the large-scale effects of the Indonesian Throughflow (Schneider, 1998). Despite the importance of the regional climate, new studies are showing that global climate models (GCMs) poorly simulate the short-term (notably diurnal) characteristics of rainfall and evapotranspiration within the region (Dai, 2001; Slingo *et al*., 2003). This has been difficult to rectify, in part, because of the lack of subdaily observations of rainfall and evapotranspiration within this and other humid tropical regions (Sorooshian *et al*., 2002; Kumagai *et al*., 2004). The Southeast Asian region is also subject to reversal in the monsoonal winds, which may impact on the short-term characteristics of the rainfall and associated phenomena (Bidin and Chappell, 2003), thus also warranting study.

Our work will examine the daily, hourly and diurnal patterns of rainfall incidence, and the spatio-temporal characteristics of rainstorm intensity and duration within a 5 km^2 region of Borneo Island. Where possible, the analysis will compare differences between the northeast and southwest monsoons. Given that there are so few studies addressing short-term rainfall behaviour within the humid tropics, this work has relevance elsewhere within equatorial regions, though the representativeness remains unclear (see Bonell *et al*. (2004)).

RESEARCH AREA

This rainfall study was carried out within the Malaysian state of Sabah, on Borneo Island, Southeast Asia. The 5 km^2 study region selected (5°01′N and 117°48·75′E) is 50 km inland from the eastern coast of Sabah, and contains the core study areas of the rainforest research station called the Danum Valley Field Centre (DVFC; Figure 1). The DVFC locality forms the focus of ongoing hydrological research on rainfall, throughfall and wet-canopy evaporation (Chappell *et al*., 2001; Chappell and Tych, 2002; Bidin and Chappell, 2003, 2004), soil-water regulation of landscape ecology (Gibbons and Newbery, 2003), streamflow generation mechanisms (Chappell *et al*., 1998; Chappell and Sherlock, 2005), rainfall-runoff modelling (Chappell *et al*., 1998, 1999, 2004b, 2006) and erosion (Douglas *et al*., 1999; Chappell *et al*., 2004a; Walsh *et al*., 2006). All of this work could be advanced with a better understanding of the temporal characteristics of rainfall within experimental catchments. The 5 km^2 study region comprises mostly of the 4 km^2 Sapat Kalisun Experimental Catchment (Bidin and Chappell, 2003, 2004) plus the area immediately to the west, which includes the DVFC rain-gauge (Figure 1).

The 5 km^2 study area has an undulating topography with an altitudinal range from 155 m (River Sapat Kalisun) to 435 m (Bukit Atur (BA)). The area lies within the Brassey Range of hills in eastern Sabah, where one of the highest peaks, Mount Danum, is at 1093 m a.s.l. (Marsh and Greer, 1992). Mount Danum (or 'Gunung Danum') is approximately 19·5 km southwest of the centre of the study area.

The natural vegetation of the area is 'lowland, evergreen dipterocarp' forest, with the upper canopy being dominated by *Parashorea malaanonan, Parashorea tomentella* (both white seraya), *Shorea johorensis* (red seraya) and *Rubroshorea* spp. (Marsh and Greer, 1992). The area lies within the Forest Management Unit (FMU) called the Ulu Segama Forest Reserve, where Yayasan Sabah manage the forest for commercial timber production and conservation. Within this FMU, timber extraction is by a selective logging system where only commercial timber trees with a girth greater than 0·6 m are felled. Extraction from most of our 5 km^2 area took place in 1988–89. Although the area remains essentially forested, the local 'clearfelling' of road corridors did leave clearings that allowed the use of ground-based rain-gauges (see Bidin and Chappell (2004)).

Daily rainfall has been measured at the DVFC meteorological station since 1986, and over the 18-year monitoring period (1986–2003) an average annual rainfall (AAR) of 2817 mm (σ 462 mm) has been recorded. The DVFC meteorological station (149 m a.s.l.; Figure 1) 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).

This study utilizes rainfall data primarily from the 1995–98 period, which included both the wettest and driest years in the DVFC 1986–2003 records. The water-year 1 May 1995 to 30 April 1996 was

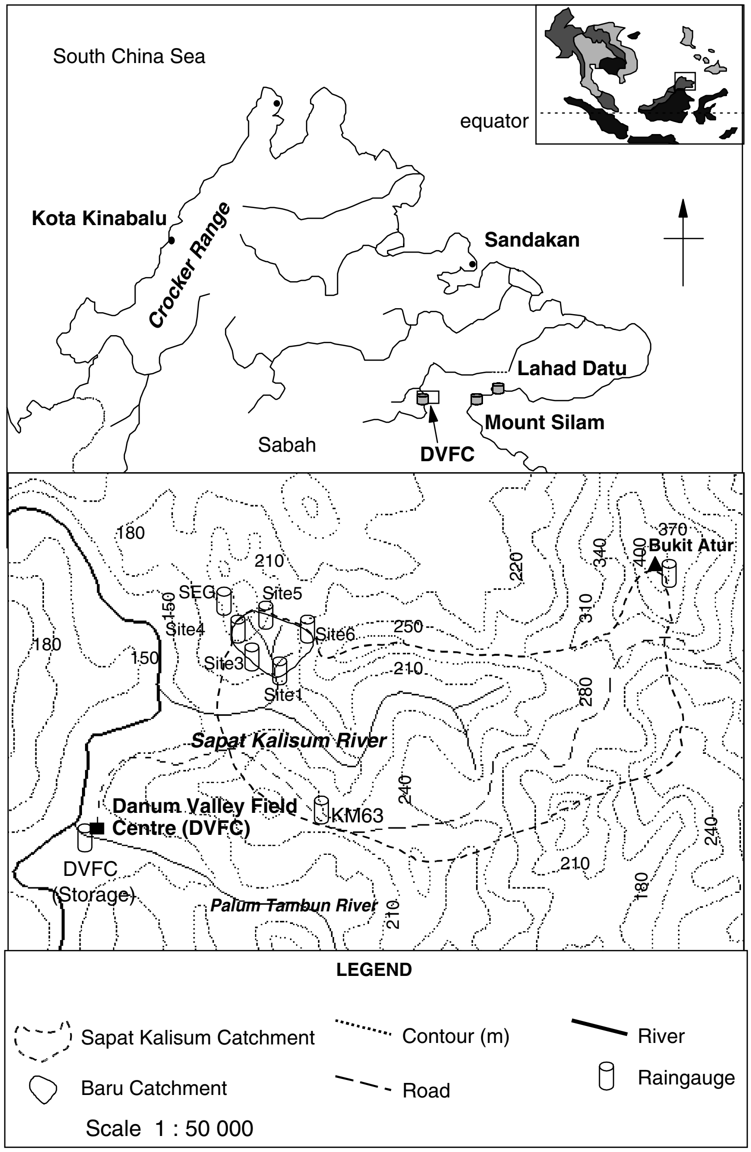

Figure 1. The location of the DVFC (5°01′N and 117°48·75′E) within northeastern Borneo and the Sapat Kalisun study area close to DVFC, including the named rain-gauges

a marked 'La Niña' wet period, with 3783 mm of rainfall or 136% AAR. In contrast, the 'water-year' 1 May 1997 to 30 April 1998, was a marked 'El Niño' period, with only 1539 mm and 55% AAR.

Air temperature and relative humidity have been measured at the DVFC meteorological station since 1986. The average daily maximum and minimum temperatures recorded between 1986 and 1991 were 30·9 °C and 22·5 °C respectively. The average relative humidity at 08 : 00 was 94·5% and at 14 : 00 it was 72% (Marsh and Greer, 1992). Evaporation pan measurements were taken from November 1997 to March 1998, when an average of 3·6 mm day^{-1} was recorded (Bidin, 2001).

INSTRUMENTATION AND MONITORING

With the exception of the rain-gauge at the DVFC meteorological station, all other rain-gauges were located within the 4 km^2 Sapat Kalisun Experimental Catchment, with most automated gauges being sited within the 0·44 km^2 tributary catchment called the Baru (Figure 1). Outflows from the Sapat Kalisun Experimental Catchment enter the River Segama, in its headwater reaches. This major river then drains to the Sulu Sea off the northeast coast of Sabah. Rain-gauges were sited at or near the ground surface at altitudes of between 132 and 436 m. For the analysis of the short-term dynamics of the rainfall within this area, up to eight recording rain-gauges were used (gauges 1, 3, 4, 5, 6, SEG, Bukit Atur, and KM63 in Figure 1) and one UK Meteorological Office Mark II storage gauge (gauge DVFC in Figure 1). The recording rain-gauges (model 103755D-04, Casella CEL Ltd, Kempston, UK) used a tipping-bucket mechanism attached to a Newlog datalogger (Technolog Ltd, Wirksworth, UK) recording the time of every 0·20 mm of rainfall. All gauges were installed in large canopy openings not less than 40 m in diameter. Gauges at sites 1, 3, 4 and 6 (Figure 1) were placed on Bornean ironwood (*Eusioderoxylon zwageri*) towers up to 6 m in height to prevent disturbance from wild boar or cover by regenerating vegetation, and the exposed site 5 gauge was located within a 2 m high and 5 m diameter chert/concrete wall to prevent elephant disturbance. The orifice of the site 5 rain-gauge was located at 0·5 m above the ground to give the minimum sky visibility of 30°, thus ensuring the wall had no significant effect (Shaw, 1993). All gauges were geo-referenced by surveying in closed-loop traverses using a TC400 Total Station (Leica Geosystems AG, Heerbrugg, Switzerland). The representativeness of the network of automated rain-gauges can be seen by observation of the records from five storage rain-gauges distributed across the Sapat Kalisun catchment (see Bidin and Chappell (2003)).

Daily data for the DVFC rain-gauge were available for the 18 calendar-year period of 1986–2003, whereas 1 min data for the KM63 rain-gauge were available for three water-years (1 May 1995 to 30 April 1998). The 1 min data for the network of eight automatic rain-gauges (i.e. gauges 1, 3, 4, 5, 6, SEG, KM63 and BA) were only available for the single water-year of 1 May 1997 to 30 April 1998, the driest year on record.

RAINFALL INCIDENCE

Characterizing rainfall incidence is important for understanding hydrological phenomena. First, the number of days with rainfall and its local spatial variability (in addition to duration of the rain events) is important for forecasting canopy wetting, and hence wet-canopy evaporation (Federer *et al*., 2003). Second, for the same hydro-geological, topographical and vegetal conditions, greater numbers of rain-days will give a more uniform riverflow regime (Blöschl and Sivapalan, 1997; Robinson and Sivapalan, 1997; Boochabun *et al*., 2004). Third, rainfall timing and duration during the day affects: (a) when vegetation canopies are wet, and thus the timing of transpiration suppression; (b) when available canopy water coincides with the available energy needed for wet-canopy evaporation (Szarzynski and Anuf, 2001; Giambelluca *et al*., 2003). Third, a strong diurnal cycle in rainfall could also give rise to strong diurnal cycle in riverflow from non-aquifers (e.g. Burt, 1979).

Rain-day patterns

Here, a rain-day has 0·2 mm or more of rainfall in 1 day. For the 18-year period 1986–2003, the DVFC rain-gauge recorded an average of 223 rain-days per annum, with a standard deviation σ of only 23 rain-days and a maximum of 256 rain-days in 1999 and a minimum of 203 rain-days in 1997. On average, rain-days were equally distributed between the northeast monsoon (November–April) and southwest monsoon (May–October) with 106 (σ 15) and 107 (σ 17) rain-days respectively. Similarly, the 6-month totals for each monsoon period in 1987–88 were almost identical, at 1315 mm in the northeast monsoon and 1323 mm in the southwest monsoon.

The spatial variation of rain-days recorded by all nine rain-gauges within the 5 km^2 region were analysed for the 1997–98 El Niño–southern oscillation (ENSO) drought period 1 May 1997 to 30 April 1998. Table I

Table I. Number n of dry and wet days for nine rainfall-monitoring sites within a 5 km^2 area (12 months' data from 1 May 1997 to April 1998). Daily totals equal to or more than 0·2 mm considered as a wet day. Rainfall totals over the 12-month monitoring period also shown

Site	Dry days		Wet days for daily totals sizes					Annual totals (mm)
	n	%	≥0·2 to ≤5 mm	>5 mm	>10 mm	>25 mm	>50 mm	
Site 6	196	53·7	100	69	40	12	2	1317·9
Site 5	196	53·7	100	67	42	12	5	1344·8
Site 4	190	52·1	106	68	43	15	5	1405·4
Site 3	201	55·1	93	71	44	15	5	1445·8
Site 1	194	53·2	112	57	34	14	2	1198·2
SEG	196	53·7	103	65	44	12	3	1307·8
KM63	190	52·1	100	73	40	20	4	1566·0
BA	161	44·1	129	74	46	10	3	1342·2
DVFC	217	59·5	73	72	47	19	3	1524·5
Average	193·4	53·0	101·8	68·4	42·2	14·3	3·6	1383·6
SD	14·6	—	14·9	5·2	3·9	3·4	1·2	114·6
CV (%)	7·6	—	14·7	7·6	9·2	23·4	34·8	8·3

shows that the frequency of dry days is comparable for gauges in the centre of the region (i.e. 190–201 days for gauges 6, 5, 4, 3, 1, SEG and KM63), but ranges from 161 days in the east (i.e. the BA gauge) to 217 days in the west (i.e. the DVFC gauge). Spatial variation in the number of wet days with a particular rainfall total was seen to increase as the daily total increased (Table I).

Figure 2a and b shows that recording a wet day (defined as having >1·0 mm rainfall) at one site whilst recording a dry day (<1·0 mm rainfall) at another site was a relatively common phenomenon for some gauge pairs within the 5 km^2 study area. For example, over the 1987–88 water-year there were 36 occasions (10% of total time) where wet days were recorded at BA but no rainfall was observed at DVFC, only 4·7 km to the southwest. Wet days were recorded at BA for 17% of the total number of dry days at DVFC. Similarly, about 22% of the annual rainfall recorded at BA occurred when DVFC was completely dry (Figure 2a). On 10 occasions when DVFC was dry, BA had daily totals greater than 10 mm (Table II). However, the 'wet and dry' phenomenon seems to be unusual for gauges less than 1 km apart, as within the 0·44 km^2 Baru catchment (Figure 2b and c, and Table II). Figure 2c, though somewhat heteroscedastic (i.e. unequal variance), shows that the number of days with some gauges measuring rainfall whilst others recorded none increased as the distance between gauges increased ($r^2 = 0{\cdot}6649$, $P < 0{\cdot}001$). The observed spottiness of daily rainfall incidence within an area of only 5 km^2 has significant implications for our ability to extrapolate plot-based estimates of wet-canopy evaporation (Chappell *et al.*, 2001; Bidin and Chappell, 2004), hillslope hydrological experiments (Chappell *et al.*, 1998; Chappell and Sherlock, 2005) or erosion (Douglas *et al.*, 1999; Walsh *et al.*, 2006) across the local region.

Rain-hour patterns

The 5-min sampled rainfall data from the KM63 rain-gauge during 1995–98 (Figure 3) were used to show those hours with or without rainfall. These data, summarized in Table III, show that the proportion of hours that received rainfall was less than 5% of the whole period, with the southwest monsoon having slightly fewer rain-hours than the northeast monsoon, particularly during the 1995–96 La Niña. This might be related to a greater presence during the northeast monsoon of the longer rain-events associated with stratiform clouds (Houze, 1977; Cifelli and Rutledge, 1994; Hong *et al.*, 1999). During the ENSO drought periods analysed (i.e. April to October 1997 and November 1997 to May 1998), less than 2% of the hour-periods had rainfall (Table II).

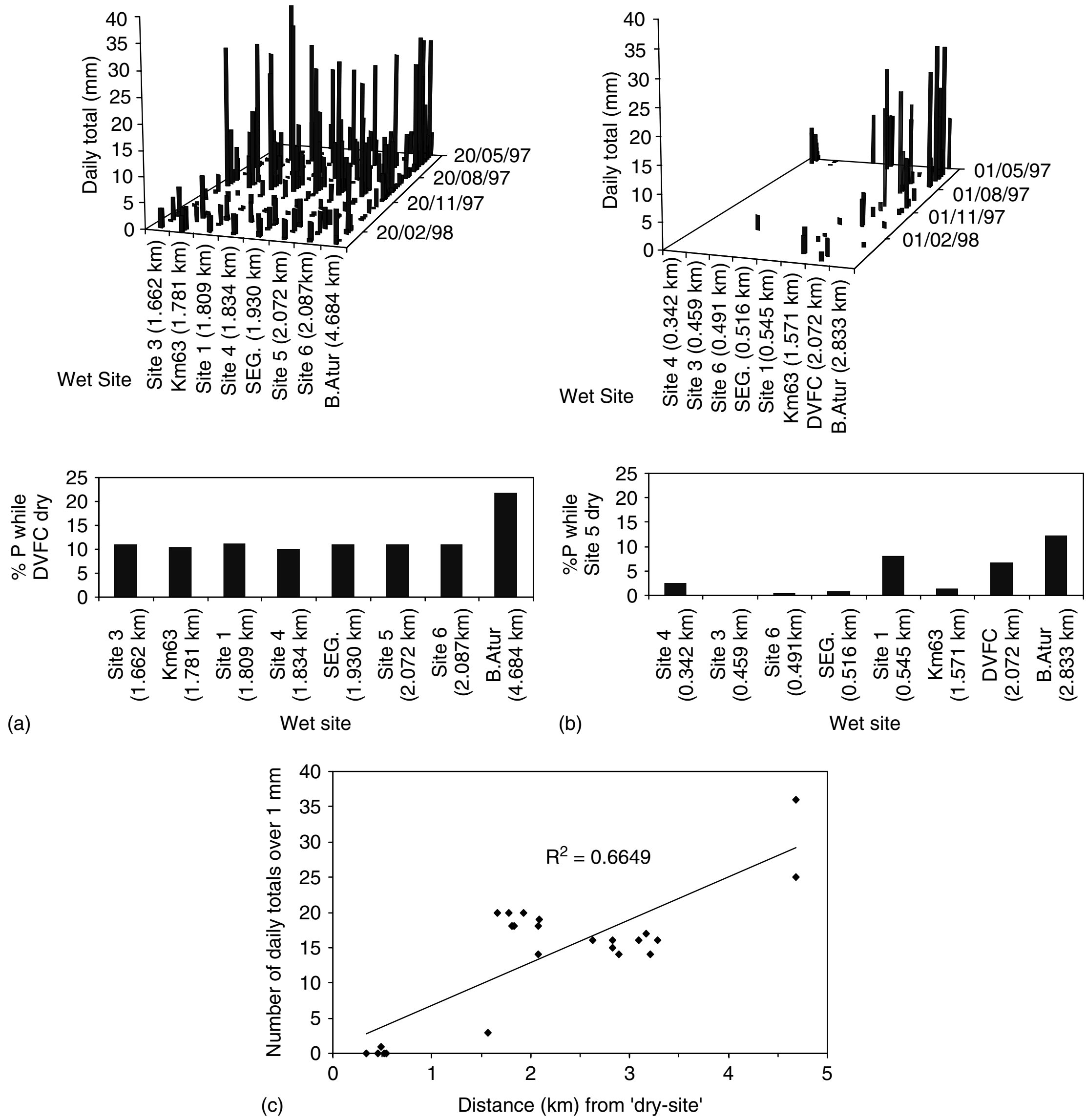

Figure 2. Wet spells for given location when dry at (a) DVFC and (b) site 5 for the period 1 May 1997 to 30 April 1998. The upper plot shows the frequency of daily totals where at least 1 mm was recorded, and the lower plot the annual percentage of rainfall total delivered at individual sites while dry at the chosen site. Values in parentheses are the distances of wet site from chosen site. (c) Relationship between number of recorded wet days (daily totals >1 mm) at particular sites when neighbouring sites were completely dry (daily total <0·2 mm) and the distance between sites

Diurnal distribution

The same 5-min data from the KM63 rain-gauge (Figure 3) were used to determine the diurnal distribution of the rainfall. Even these raw data clearly show that the afternoon has the greatest rainfall incidence. These data were, however, summarized by integrating over 2 h periods, and averages for each season calculated. The resultant graphical summary (Figure 4) clearly shows a very strong diurnal cycle, with the higher percentage of rainfall generally occurring between 14:00 and 16:00 (except for the northeast monsoon in 1997–98, when the peak is at 18:00 to 20:00). The dominance of mid-afternoon rainfall in most periods is probably

Table II. Number of rain-days recorded at particular sites (daily totals >1 mm) compared with (a) DVFC, and (b) site 5 rain-gauges when reported completely dry (daily totals <0·2 mm). Percentages of rain-days (>1 mm) over number of dry-days at DVFC are also given

	Distance from DVFC or site 5 (km)	Number of rain-days			Rain-days/dry days (%)
		>10 mm	>5 mm	>1 mm	
DVFC					
Site 6	2·087	4	8	19	9·26
Site 5	2·072	4	8	18	9·26
Site 4	1·834	3	6	18	8·33
Site 3	1·663	4	9	20	8·33
Site 1	1·809	3	6	18	9·26
SEG	1·93	4	8	20	8·33
KM63	1·781	3	9	20	8·8
BA	4·684	10	16	36	16·67
Site 5					
Site 4	0·342	0	0	0	0
Site 3	0·459	0	0	0	0
Site 6	0·491	0	0	1	0·51
SEG.	0·516	0	0	0	0
Site 1	0·545	0	0	0	0
KM63	1·571	0	0	3	1·53
DVFC	2·072	3	6	14	7·14
BA	2·833	5	8	15	7·65

the result of localized convective rain events from cumulus clouds developed by solar heating through the day (Battan, 1979; Riehl, 1979). Similar mid-afternoon peaks are seen at other inland tropical localities in Peninsular Malaysia (Ramage, 1964; Oki and Musiake, 1994; Sorooshian *et al.*, 2002) and the Amazon (Lloyd, 1990). This contrasts with the oceans (and small islands), which show an early morning rainfall peak, due to nocturnal cooling or sea–air temperature differences (Sorooshian *et al.*, 2002; Bonell *et al.*, 2004). Coastal regions have diurnal distributions that either include elements of both land and ocean phenomena (Chen and Houze, 1997) or a distinctive regime resulting from the effects of land and sea breezes (Ramage, 1964; Sorooshian *et al.*, 2002). Figure 4 also shows that, in all years, there are greater morning rainfalls during the northeast monsoon in comparison with the southwest monsoon. This again may be the result of greater amounts of rainfall from stratiform systems in the northeast monsoon (Cifelli and Rutledge, 1994), or might relate to showers being brought from the east coast of Sabah 50 km away during the northeast monsoon (see Watts, 1955). Additionally, the simple unimodal diurnal cycle (Figure 4) does, however, appear to be disrupted during the northeast monsoon in 1997–98 at the trough of the ENSO cycle (e.g. Chappell *et al.*, 2001; Tangang, 2001; Chappell and Tych, 2002; Boochabun *et al.*, 2004).

RAIN-EVENT INTENSITY AND DURATION

Rainfall intensity and storm duration monitored at the KM63 gauge during 1995–98 were analysed. A characterization of the intensity of storms over very short periods is necessary to understand the likelihood of infiltration-excess overland flow, and hence the presence of widespread rill or gully erosion (Van der Plas and Bruijnzeel, 1993; Godsey *et al.*, 2004; Morgan, 2004). As storm duration is one of the factors affecting river hydrograph shape, it is also important for the understanding of differences in rainfall-runoff response between different catchments (Pearce *et al.*, 1982; Kokkonen *et al.*, 2003).

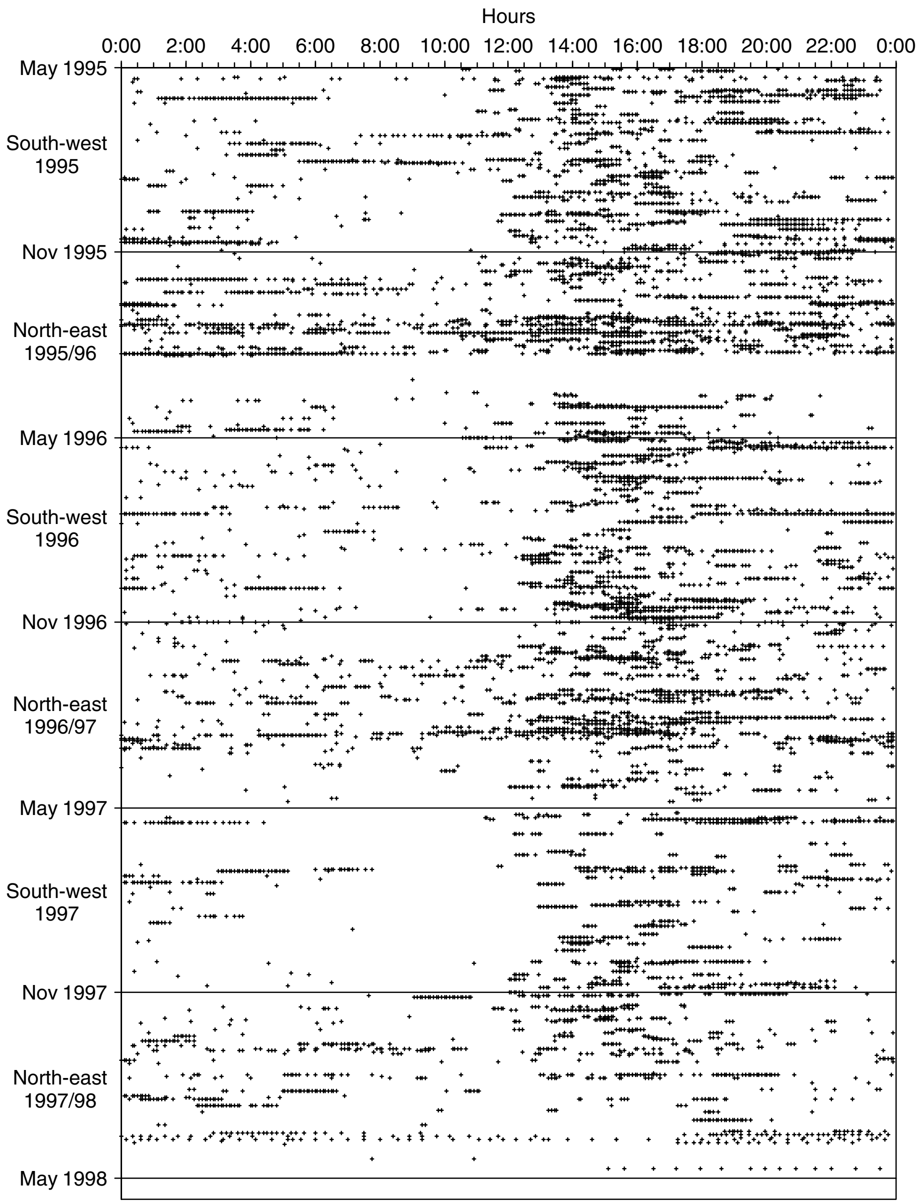

Figure 3. Presence and absence of rain events at KM63 near DVFC within the period from 1 May 1995 to April 1998. Each data point represents a 5 min interval with at least 0·2 mm of rain recorded, and each row represents a different day

The 5-min intensity

In only 1·1% of the 5 min periods of the 3-year data set were two or more 0·2 mm rain-gauge tips recorded, so intensities <4·8 mm h^{-1} sampled on 5 min periods dominated the time-series. For only 0·09% of the time did rainfall intensity exceed 50 mm h^{-1} equivalent per 5 min period. The peak intensity monitored in any 5 min period of the 3 years (May 1995 to April 1998) was 73·7 mm h^{-1} equivalent. This short-term intensity is, however, much smaller than peak intensities monitored in French Guyana, with its similar non-cyclonic rainfall regime or in the cyclone-affected region of northeast Queensland, Australia (see Bonell *et al*. (2004);

Table III. Total hours of actual rainfall at the KM63 rain-gauge. The rainy hours are comparable for the southwest (SW) and northeast (NE) monsoons for each annual season

Period	1995–96		1996–97		1997–98	
	Rainy hours	Wet spells[a] (%)	Rainy hours	Wet spells[a] (%)	Rainy hours	Wet spells[a] (%)
SW	158·7	3·59	142·4	3·23	81·7	1·85
NE	187·3	4·27	152·1	3·50	81·9	1·89
Total	346		294·5		163·6	

[a] Percentage duration of wet spells over the respective monitoring periods.

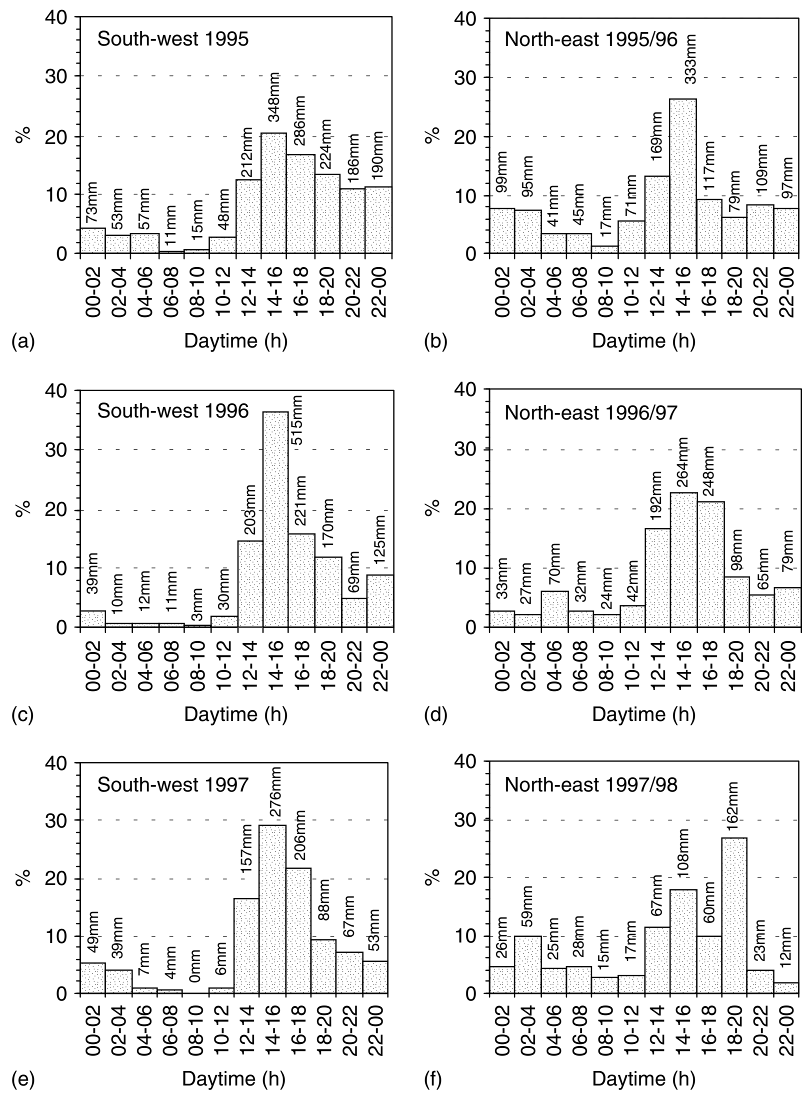

Figure 4. Diurnal distribution of rainfall for different monsoon period recorded at KM63 site

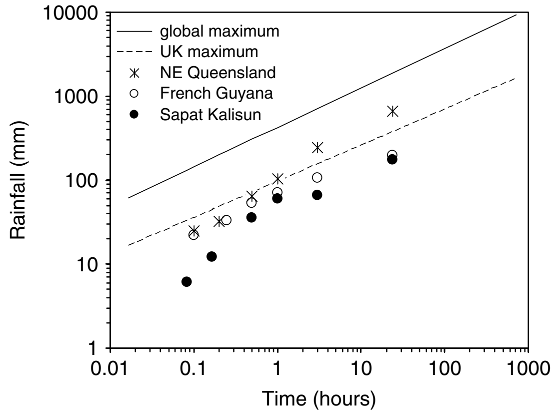

Figure 5. Sampling duration against maximum rainfall total recorded. Filled circles show the data for the Sapat Kalisun catchment during the 1 May 1995 to April 1998 period for durations up to 6 h and from the 1986–2003 records for a 1 day duration. Data for 6 min, 12 min, 30 min, 1 h, 6 h and 1 day from non-cyclonic French Guyana and cyclonic northeastern Queensland (from Bonell *et al.* (2004)) are shown with open circles and asterisks respectively. The relationship between maximum rainfall total and sampling period for the globe and temperate UK (from Shaw (1993)) are shown with a solid line and broken line respectively

Figure 5). In part, the lower peak intensity may be due to analysis of only 3 years of 5 min sampled data. Figure 5 also shows that lower peak intensities for sampling periods of 10 min, 30 min, 1 h and 3 h are seen for the Sapat Kalisun in comparison with the two other tropical sites. The peak daily intensity of 177 mm for DVFC over the 1986–2004 period (Douglas *et al.*, 1999) is shown in the same figure. This peak daily intensity is comparable to that recorded in the other non-cyclonic region, but much less than that recorded for cyclonic northeastern Australia, the global maximum or even the maximum for temperate UK (Figure 5).

The almost complete absence of 5 min periods with >50 mm h^{-1} equivalent rainfall events explains why the soils of the Sapat Kalisun catchment, with their mean topsoil permeability of 500 mm h^{-1} (Chappell *et al.*, 1998), fail to generate significant volumes of infiltration-excess overland flow (see Chappell *et al.* (1999, 2004a, 2006)).

Rain-event (storm) duration

For the analysis of storm duration, storm events were delimited by periods of 20 min or more without a rain-gauge tip (i.e. $\geq$0·2 mm rainfall). The duration of all storm events recorded at the KM63 gauge during the November 1997 to May 1998 and April to October 1998 monsoon periods delimited by this criterion were defined and are summarized in Figure 7. During the 1997–98 northeast monsoon drought period, 78% of all events lasted for less than 15 min, in comparison with 52% of all events in the 1997 southwest monsoon. Almost all rainfall was delivered within the first 80–100 min of each event (Figure 6). The short duration of the storms in the Sapat Kalisun catchment, combined with the non-aquifer geology and small size (i.e. 4 km^2), explains the flashy nature of the stream hydrographs observed in this catchment (see Chappell *et al.* (1999, 2004a, 2006)).

Local spatial variation in rain-event duration and intensity

Cross-correlation (May and Julien, 1990) between four rain-gauges within the 5 km^2 study region (i.e. rain-gauges 5, 6, KM63, and BA) was undertaken for two example storms. The objective of this analysis was to identify the correlation between pairs of rainfall time-series. The rainfall rate r at rain-gauge location G_i is a function of space and time ($r(G_i,\ t)$); thus, the cross-correlation is given by

$$\rho_\gamma(G_1, G_2) = \frac{1}{n-\gamma}\sum_{k=1}^{n}\frac{[r(G_1, t_k)\delta_k - r(G_1)][r(G_2, t_{k+\gamma})\delta_k - r(G_2)]}{S(G_1)S(G_2)}$$

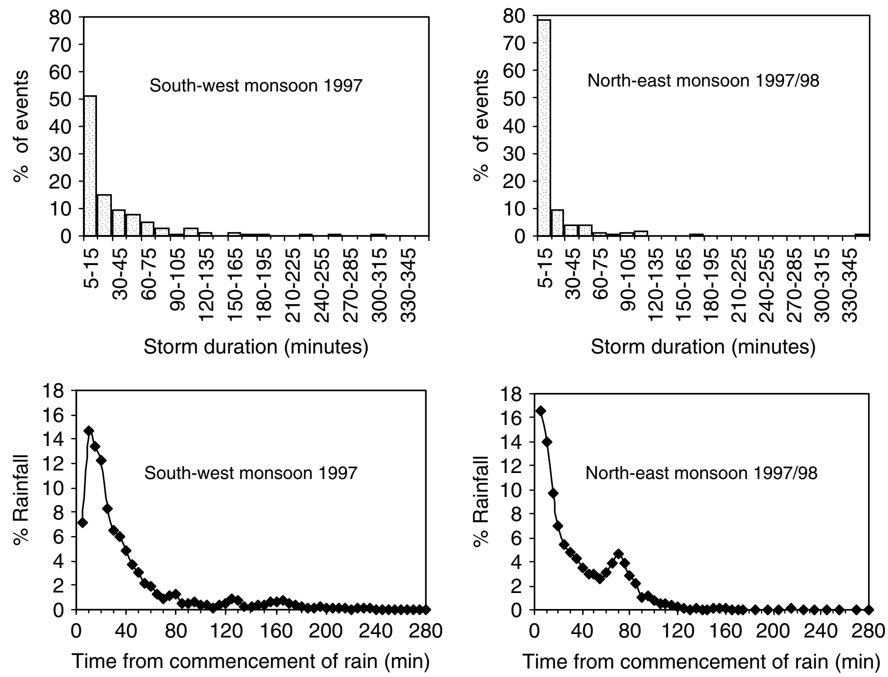

Figure 6. Rainfall events storm duration for different monsoon periods as indicated in each graph recorded at site KM63

where ρ_γ is the correlation coefficient at lag γ, t_k is the kth time step, δ_k is a rainfall indicator, n is the record length at zero lag, r is the mean of the time series and S is the biased estimate of the standard deviation (Messaoud and Pointin, 1990; Goodrich *et al.*, 1995). The rainfall indicator δ_k is designed to suppress long periods with no rainfall. It is equal to zero when both rates are zero, and unity in other cases (Messaoud and Pointin, 1990; Goodrich *et al.*, 1995).

Each time-series was compared with the other three time-series, giving nine pairs in total. The distance between each gauge pair selected was between 0·5 and 3·2 km. Two different types of rain event were selected for analysis: (i) a late-afternoon convective event observed on the 11 July 1997; (ii) a rain event produced by stratiform clouds (classified by non-routine observations at the DVFC meteorological station). The stratiform event was observed on 18 May 1997 and was the longest (continuous) rain event observed during the 1997–98 monitoring period.

The example convective event lasted from as short as 72 min at the BA rain-gauge to 200 min at KM63. At some locations, this event was longer than the typical afternoon convective events (Figure 6), but it was selected to allow different integration periods to be examined in the cross-correlation analysis. The rainfall total for this event ranged from only 6 mm at the BA rain-gauge to 41 mm at site 6, and 65 mm at KM63. In some contrast, the rainstorm produced from stratiform clouds lasted for a very similar time-period at all rain-gauges, i.e. 269 to 278-min. Rainfall depths for this stratiform event ranged from 46 mm at the KM63 gauge to 52 mm at the BA gauge.

Correlograms of the cross-correlation coefficients and lag times were computed and plotted for each gauge pair for rainfall integrated over time-steps of 1, 5, and 15 min. This transformation effectively produced a new time-series with a different temporal resolution (May and Julien, 1990).

It was found that this 'time-distribution pattern analysis' for the convective rain event was best described by a 1 min event data series (Figure 7). A longer time resolution produced an unreliable correlogram model due to the short duration of the event (see McCuen and Snyder (1986)). Indeed, McCuen and Snyder (1986) recommend that the magnitude of lag γ should be limited to about 10% of the record length n at ρ_o. Once

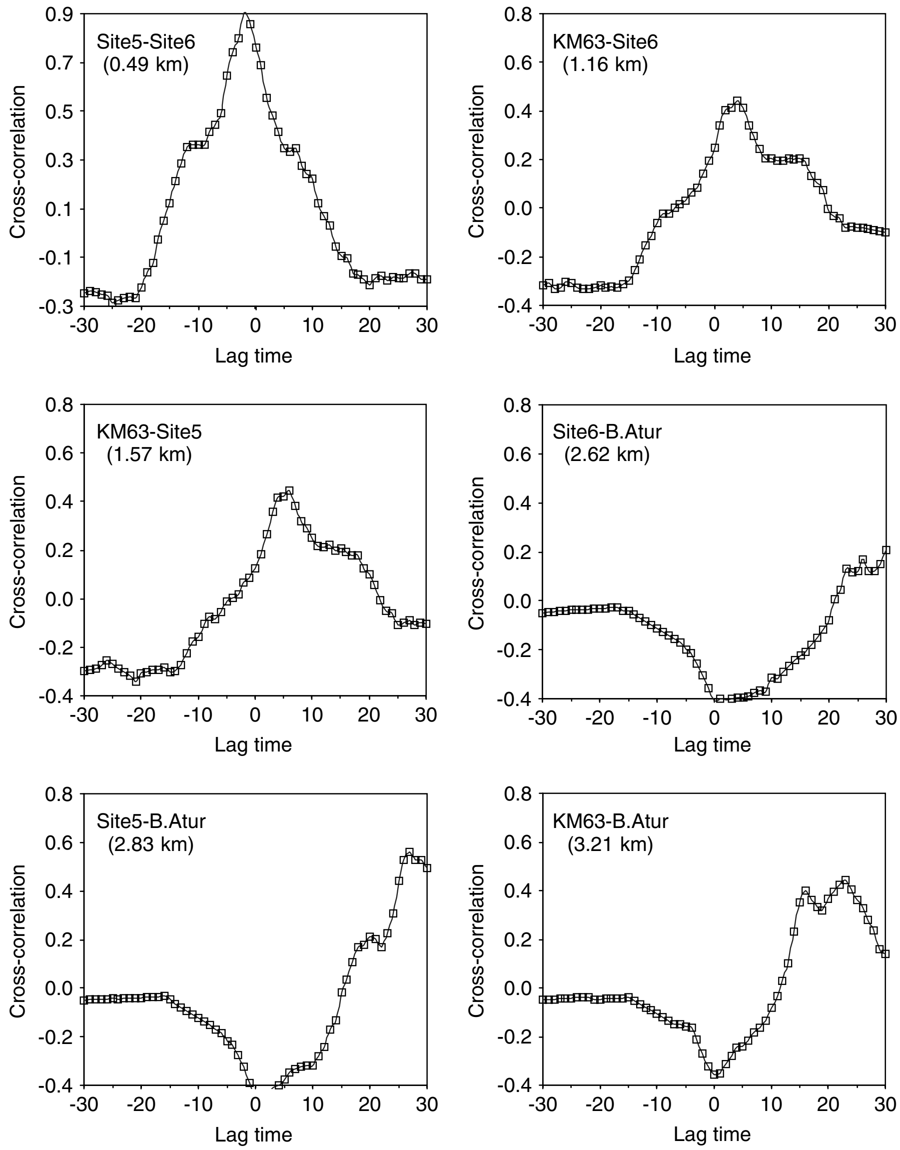

Figure 7. Correlograms for the site pairs for the 1 min interval convective event on 8 July 1997 (in the southwest monsoon). Site locations are shown in top left of each graph

γ exceeds this empirical limit, the correlograms may begin to oscillate. For the present analysis, a maximum lag time of 30 time-steps was chosen.

Excluding the three gauge pairs that include the BA gauge, the 1-min correlograms for the convective event have sharp peaks (Figure 7). Moreover, the loss of intergauge correlation during the convective event is comparable to that observed during five convective storms in Arizona studied by Goodrich *et al*. (1995). Cross-correlation in the Sapat Kalisun convective event reduced by 0·04 correlation units per minute (Figure 7), whereas Goodrich *et al*. (1995) observed a range of 0·04 to 0·11 correlation units per minute. This again provides quantitative evidence for the convective events in the Sapat Kalisun having a small spatial extent and short duration.

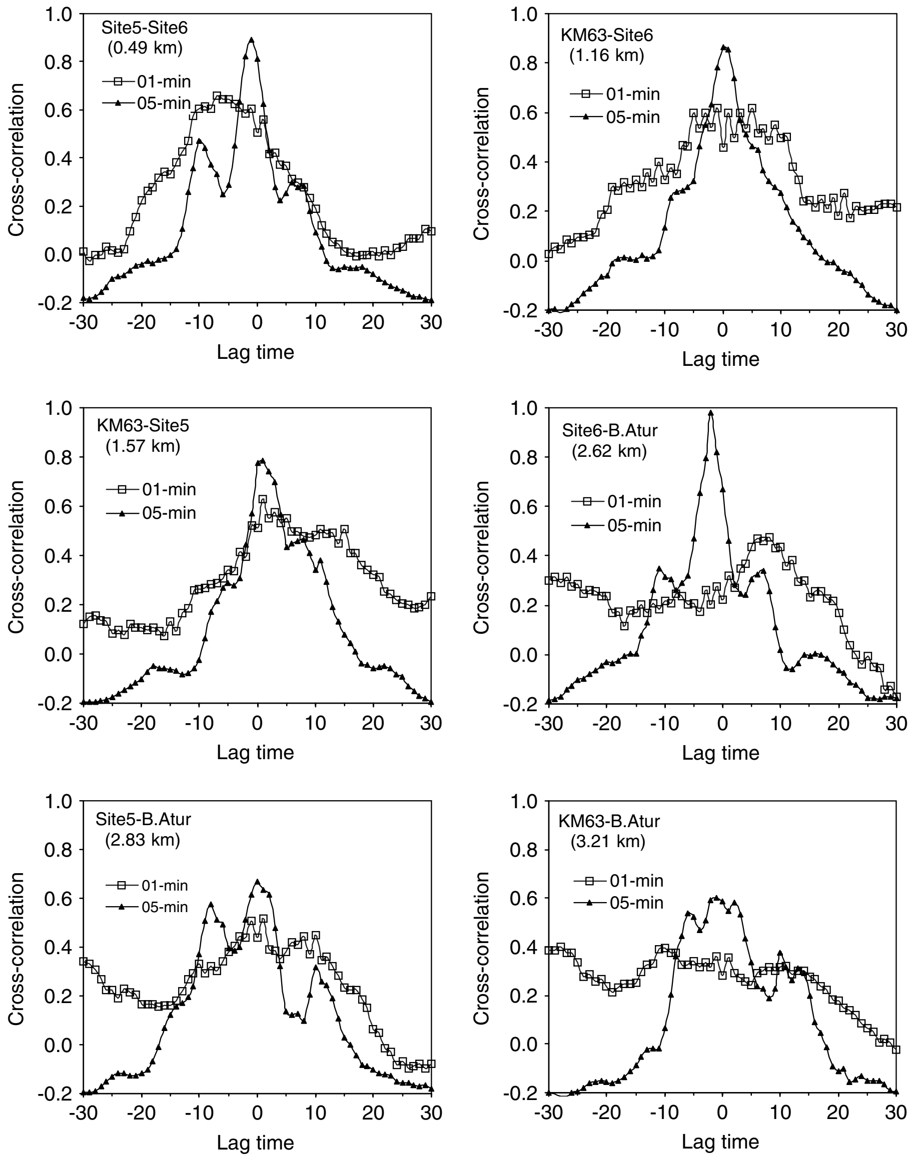

Figure 8. Correlograms for the site pairs for the stratiform event on 18 May 1997 showing both 1 min and 5 min recording intervals. Site locations are shown in top left of each graph

Comparison of the 1-min correlograms from both the convective event (Figure 7) and the stratiform (Figure 8) event shows, quantitatively, that the stratiform event has a slightly longer duration and larger spatial extent. This is also shown by the fact that a longer sampling interval (i.e. lag time) of 5 min rather than 1 min gives more reliable correlograms for the stratiform event (Figure 8). Thus, 5-min resolution data may be acceptable for fully distributed rainfall-runoff modelling of the 4 km^2 Sapat Kalisun catchment during stratiform events, but 1-min resolution data may be needed for convective events (see Moon *et al*. (2004) and Smith *et al*. (2004)).

The shift in the peak of the convective-event correlograms that include the BA rain-gauge (Figure 7) may indicate: (i) rainfall over BA is produced by a different cloud mass to that over KM63, sites 5 and 6 within the centre of the catchment (see Bidin and Chappell (2003)), and that this cloud releases rainfall 20–30 min after that in the centre of the catchment; or (ii) a local cumulus cloud over the centre of the Sapat Kalisun catchment has moved towards BA with an airflow from the southwest at a rate of 2 m s^{-1} (see Bidin and Chappell (2003)). In 1997–98, wind speed records were not available for the lower atmosphere around BA; anemometer arrays were, however, installed in late 2004, which will allow us to test this second hypothesis in the future.

CONCLUSIONS

This inland, equatorial location appears to receive most of its rainfall in low intensity events that have a relatively low peak intensity in comparison to other tropical sites. Comparing these low rainfall intensities with the near-surface permeabilities measured within the immediate locality (i.e. geometric mean of ~500 mm h^{-1}; Chappell *et al*., 1998), large quantities of infiltration-excess overland flow would not be expected. Indeed, surface-flow monitoring within the catchment by Chappell *et al*. (1999, 2004a, 2006) indicated that less than 5% of the rainfall entered the streams as overland flow. This is contrary to popular view of stream hydrographs in the humid tropics being dominated by water from infiltration-excess pathway (e.g. Sani, 1998).

Storm durations (where storms are separated by >20 min without 0·2 mm of rainfall) are typically short, particularly during the 1997–98 northeast monsoon, where 78% of all rainfall was delivered within events of <15 min duration. Such a situation would be consistent with the observation that most rainfall is delivered in localized (Bidin and Chappell, 2003) mid-afternoon events from cumulus clouds that have developed during the day. The typical short duration of the events, together with the non-aquifer geology and small catchment size, explains the flashiness of the river hydrographs monitored within the Baru catchment tributary of the Sapat Kalisun (Bidin and Greer, 1997; Chappell *et al*., 1999) if compared with similar catchments but with long duration rain-events in temperate UK (Chappell *et al*., 2006). Analysis of Sapat Kalisun rain events in La Niña periods would strengthen these conclusions.

The localized nature of the rain events within the Sapat Kalisun catchment can be seen in the temporal pattern of the rainfall incidence. Rain-gauges that are less than 1 km apart tend to experience rainfall on the same days. As gauge spacing increases to 2–4 km apart, then rainfall is not received on the same days for some 15–30 days in the year. Loss of intergauge correlation is most strongly seen during the mid-afternoon convective event analysed, where temporal intergauge correlation falls off in minutes even for gauges a few hundred metres apart. In contrast, the stratiform event analysed lost temporal intergauge correlation perhaps by a factor of five more slowly. The short duration and localized nature of the convective events within the 4 km^2 Sapat Kalisun catchment, therefore, demand not only a dense rain-gauge network, but also a high temporal sampling intensity. Indeed, Chappell *et al*. (1999, 2006) found that they needed a 5 min sampling intensity to model the rainfall-streamflow characteristics within small tributaries of the Sapat Kalisun.

In summary, if rainfall-runoff modelling of a small (i.e. <10 km^2) experimental catchment within the humid tropics is the goal (see Chappell *et al*. (1999, 2006)), then rainfall may need to be monitored at a very high sampling frequency of every 5 min or less across a very dense network of at least one rain-gauge every kilometre.

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