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TEMPORAL VARIATION IN THE STABLE ISOTOPES IN PRECIPITATION RELATED TO THE RAINFALL PATTERN IN A TROPICAL RAINFOREST IN PENINSULAR MALAYSIA

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We present the temporal variability of the oxygen ($\delta^{18}O$) and hydrogen (δ^2H) isotope signatures in precipitation at Pasoh Forest Reserve (FR), a tropical rainforest in Peninsular Malaysia. We investigated the daily and seasonal variability of stable isotope signatures in precipitation, particularly in relation to the effects of monsoon seasons, rainfall characteristics and larger scale trends compared with those at nearby Global Network of Isotopes in Precipitation (GNIP) monitoring stations. The isotope signatures did not differ between monsoon seasons but were correlated with amount of rainfall, its intensity and duration. The effect of amount of rainfall on isotope composition was clearly detected and comparable with long-term mean monthly statistics of nearby GNIP stations. Unfortunately the effect was obscured at the daily timescale and, for monthly rainfall, not averaged over the long-term. No large deuterium excess was detected at the daily timescale for small-scale rainfall events. The $\delta^{18}O$ in precipitation water was more closely correlated with the 60-day antecedent rainfall index than with the amount of rainfall each day. These findings suggested that the isotopic composition in the study area was the result of a rainout on a larger scale in addition to the local scale and specific rain events.

Keywords: South-west monsoon, north-east monsoon, antecedent precipitation index, deuterium excess, Global Network of Isotopes Precipitation (GNIP)

INTRODUCTION

One of the greatest concerns related to maintaining the Malaysian tropical rainforest ecosystem is the change in rainfall pattern and amount because it will eventually change the microclimate, evapotranspiration, soil moisture, carbon flow and tree density. Compared with Amazonian forest, South-East Asian rainforest does not experience distinct dry and wet seasons during the year, although dry and wet periods do occur with considerable variability between years (Tani et al. 2003, Kumagai et al. 2005). Stable isotope signals in precipitation water serve as indices of site-dependent rainfall and climate characteristics. They can be also used as tools for monitoring possible climate change. Therefore, in our effort to conserve the Malaysian tropical rainforests, it is very important to record stable isotope signals in precipitation water. These records can also serve as basic information for regional research. The use of dual isotope (oxygen ($\delta^{18}O$) and hydrogen (δ^2H)) approach in this study could systematically help in distinguishing distinct water pools in the forest ecosystem. These pools mainly include (1) water used by trees and not contributed to stream flow and (2) mobile water unrelated to water used by trees (i.e. groundwater, streamflow, infiltration and hillslope runoff) (McDonnell 2014). This will improve understanding of the ecohydrological processes controlling water flow in the soil–plant–atmosphere continuum (Berry et al. 2016). In this paper, we report only the isotope properties of rainfall received by Pasoh Forest Reserve (FR) to have an understanding of the isotope in rainwater. The result from this study will later be used to estimate tree water use and soil water in Pasoh forest.

This study examined stable isotopes in precipitation water. A water molecule consists of one oxygen atom and two hydrogen atoms. Hydrogen and oxygen each have several naturally occurring isotopes. The stable isotopes of oxygen are ^{18}O, ^{17}O, and ^{16}O and those of hydrogen are ^{1}H and ^{2}H. The stable isotope ratios in water are expressed relative to an internationally accepted standard material for hydrological application, the Vienna Standard Mean Ocean Water (Gonfiantini 1978). According to this standard, the isotopic ratio is defined using delta notation as:

$$\delta = (\text{R sample} - \text{R standard}) / (\text{R standard}) \times 1000$$

where δ = isotopic ratio and R = ratio of heavy to light isotopic ratio. This equation can be used to calculate the ratio of $\delta^{18}O$ and $\delta^{2}H$. Delta values are often expressed in permil (‰). Changes in $\delta^{18}O$ and $\delta^{2}H$ occur during the condensation process, where water vapour loses its heavy components and the $\delta^{18}O$ and $\delta^{2}H$ values become more negative as condensation continues.

The use of oxygen isotopes in paleoclimatology was reported in the first analysis of the Global Network of Isotopes in Precipitation (GNIP) due to the composition of meteoric precipitation, which exhibited variation based on temperature, altitude, continental and rainfall amount effects (Dansgaard 1964, Clark & Fritz 1997, Ingraham 1998). The effect of temperature on isotope composition typically occurs in temperate and high-latitude regions but not in tropical regions. Isotopic values of rainfall decrease when water vapour moves from lower to higher elevation. This is known as the altitude effect. Isotopes get progressively lighter as clouds move towards high altitudes and precipitation occurs. The continental effect (i.e. water vapour moving over large areas throughout continent) consists of storm routes carrying water vapour from their origin and the distance to the destination. The variability in the continental effect is driven by variation in source regions of moisture, air mass transport pathways and precipitation history (Dansgaard 1964, Araguás-Araguás et al. 2000). Isotope values decrease with increasing amounts of rainwater. This decrease is also influenced by seasonal variation in the isotopic composition of precipitation because large and small amounts of rainfall also show seasonality (i.e. monsoon seasons and wet and dry seasons). The relationship between $\delta^{18}O$ and $\delta^{2}H$ in precipitation compared with the Global Meteoric Water Line (GMWL) is also used to analyse the source of rainfall. The best-fit equation for GMWL is expressed as $\delta^{2}H = 8 \times \delta^{18}O + 10$ for all data points (Dansgaard 1964). Deuterium excess is useful for interpreting the hydrological cycle in the atmosphere. For example, increased deuterium excess in precipitation can arise from the addition of re-evaporated moisture from continental basins to the water vapour travelling inland (Kondoh & Shimada 1997). Several studies have examined the isotope composition of precipitation in South-East Asia. Seasonal $\delta^{18}O$ values are negatively correlated with monsoon strength over almost the entire Asian countries experiencing monsoon season, indicating that the stable isotope composition of precipitation is more depleted during intense monsoon seasons and more enriched during weak monsoon seasons (Vuille et al. 2005). Variation in seasonal isotopes in precipitation in subtropical and tropical regions does not reflect the degree of rainout at a cloud scale but rather at the regional scale (Kurita et al. 2009).

Information on variation in isotopes in precipitation in South-East Asia has increased. However, no study has been performed on the rainforests in Peninsular Malaysia as a possible indicator of local climate phenomena. Information in this area is needed to understand the symptoms of climate change in tropical rainforests in this area. We studied isotope signals in precipitation at Pasoh FR, a tropical rainforest in Peninsular Malaysia, to understand their characteristics. These data are fundamental and useful for future studies related to forestry and climate change in the region. The origin of monsoonal precipitation is likely to vary due to location of the study area. If monsoonal rainfall is considered, the water vapour could be originating from the ocean. However, this assumption must be empirically investigated because the area is subjected to two monsoonal seasons, namely, north-east (NE; November–March) and the south-west (SW; May–September), while April and October are intermonsoon periods. These seasons may have different isotopic signatures, marked by different water sources in the area. Other factors, such as local rainfall characteristics, the reuse of land-originating re-evaporated moisture, larger scale atmospheric conditions and the El Niño Southern Oscillation may also be related to variation in the isotopes of precipitation. In this study, we investigated the daily, seasonal (four seasons annually, i.e. NE monsoon, first intermonsoon, SW monsoon and second intermonsoon) variability of stable isotope signatures in precipitation with specific consideration given to the effects of monsoon season, rainfall characteristics and larger scale trends compared with nearby GNIP monitoring stations in Peninsular Malaysia, Singapore and Bangkok, Thailand.

MATERIALS AND METHODS

Site description

The study was conducted at Pasoh FR (Figure 1a) located at 2° 58' N, 102° 18' E at approximately 75–150 m above sea level. It is a lowland dipterocarp forest with 30–40 m canopy height (emergent trees at ~45 m). The core area (600 ha) of the reserve is primarily lowland mixed dipterocarp forest, consisting of various *Shorea* and *Dipterocarpus* species. Details of the vegetation, micrometeorology and eddy flux measurements are described in our previous studies (Kosugi et al. 2008, 2012). Mean annual rainfall at the study site was 1801 mm (1996–2015), peaking in March–May and October–December (Kosugi et al. 2008) and was characterised by its short duration and high intensity (Noguchi et al. 2003). Mean annual air temperature was 25.4 °C (1997–2011) (Noguchi et al. 2016).

Rainfall measurement and isotope analysis

Rainfall was measured at 30-min intervals using a 0.5-mm tipping bucket rain gauge. Rainfall data were collected using storage type and tipping bucket rain gauges in an observatory located 430 m away from the flux tower. The storage rain gauge was buried in the ground to prevent heating which would cause evaporation. A double-layered small-mouth inner glass bottle was also used to prevent evaporation. Water samples for the isotope analysis were collected daily from this bottle at 8–9 a.m. (solar noon in this area is 1 p.m.), using 10-mL polyethylene terephthalate or glass bottles with no air space to prevent evaporation. Rain water samples were collected from 5 September 2012 till 29 December 2015. Rainwater samples were filtered using 13-mm 0.45-µm phobic polytetrafluoroethylene filters and transferred to a 2-mL vial. A cavity ring-

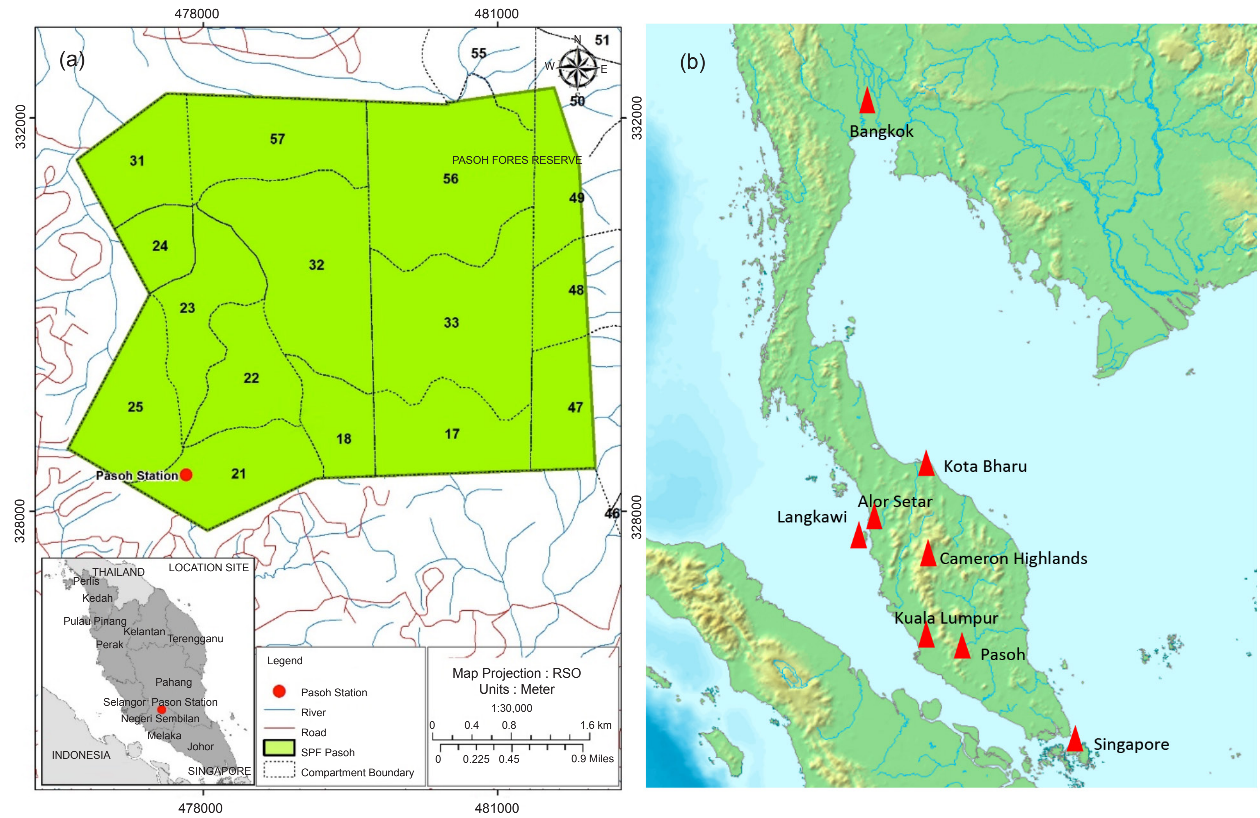

Figure 1 Location of the rainwater isotope monitoring stations at (a) Pasoh FR and (b) neighbouring Gobal Network of Isotopes in Precipitation stations; numbers show forest compartments

down spectrometer was used to analyse isotope composition in the rainwater samples. The laboratory had a device with specific analytical precision of 0.06‰ for $\delta^{18}O$ and ≤ 0.11‰ for $\delta^{2}H$ (Katsuyama 2014). We also determined the deuterium excess value for each rainwater sample. The deuterium excess (d) was defined as (Dansgaard 1964):

$$d\ (‰) = \delta^{2}H - 8 \times \delta^{18}O$$

and was an index of deviation from the GMWL which has a deuterium excess value of 10‰ (Froehlich et al. 2002). A total of 465 samples were collected throughout the study period. Samples collected with more than a 1-day interval or with < 0.5 mm rainfall were omitted from the analysis. In all, 333 samples were analysed for isotopic composition. We assumed that these samples were not affected by evaporation during storage because most rainfall at the site occurred from evening till midnight and the storage rain gauge was carefully designed to prevent evaporation.

The daily amount of rainfall, maximum rainfall intensity and duration were calculated for each 24-hour period (8 a.m. till 8 a.m. the next day to correspond with rainwater sampling). Maximum rainfall intensity was the maximum value that occurred during a 30-min period of each day. Duration was calculated by counting the number of rainfall events in one day using a 30-min interval dataset. Generally, in Malaysia, the NE monsoon brings heavy rain, particularly to the states on the east coast of Peninsular Malaysia and western Sarawak. We divided each year into three seasons, namely, SW and NE and intermonsoons to investigate differences between monsoon seasons.

We compared our data with larger scale, long-term mean monthly isotope and rainfall data collected from five stations in Peninsular Malaysia (Kuala Lumpur, Cameron Highlands, Kota Bahru, Alor Setar and Langkawi) and two stations (Singapore and Bangkok) from neighbouring countries (Figure 1b and Table 1). These data were obtained from the Atomic Energy Agency–GNIP database (available at https://nucleus.iaea.org/wiser/gnip.php). To investigate the antecedent rainfall conditions, we used the 60-day antecedent rainfall index (API60) defined as:

$$\sum_{i=1}^{60} P_i / i$$

where P_i = daily precipitation (mm) and i = the number of preceding days (Kosugi et al. 2007). The API60 indicated the seasonal rainfall pattern including antecedent conditions at the study site. The API60 was used in this study because it was tested beforehand and gave the highest correlation with isotopes among several antecedent rainfall indices. With API60, we knew whether a specific date was at the beginning or in the middle of the rainy season. We also used a 30-day running average of API60 to show the monthly scale trend excluding the daily scale trend.

RESULTS

Rainfall characteristics

Monthly rainfall varied from 6 to 367 mm month^{-1} (June 2012 and November 2015 respectively) during the four years of study (Figure 2a). Pasoh FR experienced two major peaks of monsoonal rainfall in April–May and October–December to form a bimodal pattern. Rainfall varied considerably between years. The seasons occasionally changed in July and August. Heavier rainfall occurred during the NE monsoon than during the SW monsoon season (Figures 2a and b). Most of the rain fell from late afternoon till midnight (Figure 2c), and rainfall frequency increased during this time. Amount and rainfall events peaked around evening, but they were little and rare in the morning. Relatively small amount of rainfall (1–4 mm day^{-1}) was collected during the NE and SW seasons (Figure 2d). The most frequent maximum rainfall intensity in one day was 1–3 mm 30 min^{-1} (Figure 2e), and the most frequent duration of rainfall in a day was 1.5–2 hours (Figure 2f). Rainfall at the study site was characterised as relatively small amount and of short duration, though sometimes larger amount of rainfall with longer duration occurred. The NE monsoon season had greater number of rainfall events with some events of being longer than the rest.

Distribution of isotope values in precipitation

Means and standard deviations of daily $\delta^{18}O$, $\delta^{2}H$ and deuterium excess values were -5.90 ± 3.0 (median = -5.40), -35.4 ± 24.1 (-31.5) and 11.7 ± 3.0 (11.9) respectively. Daily means and standard deviations of $\delta^{18}O$ and $\delta^{2}H$ values for

Table 1 Details of the five Global Network of Isotopes in Precipitation (GNIP) monitoring stations in Peninsular Malaysia (Kuala Lumpur, Cameron Highlands, Kota Bahru, Alor Setar and Langkawi) and two nearby stations (Singapore and Bangkok)

Station	Latitude (N)	Longitude (E)	Elevation (m)
Pasoh	2° 58'	102° 18'	75
Singapore	1° 21'	103° 54'	32
Bangkok	13° 43'	100° 30'	2
Kuala Lumpur	2° 53'	101° 46'	26
Cameron Highlands	4° 28'	101° 22'	1430
Alor Setar	6° 11'	100° 24'	5
Langkawi	6° 19'	99° 43'	31
Kota Bahru	6° 9'	102° 16'	7

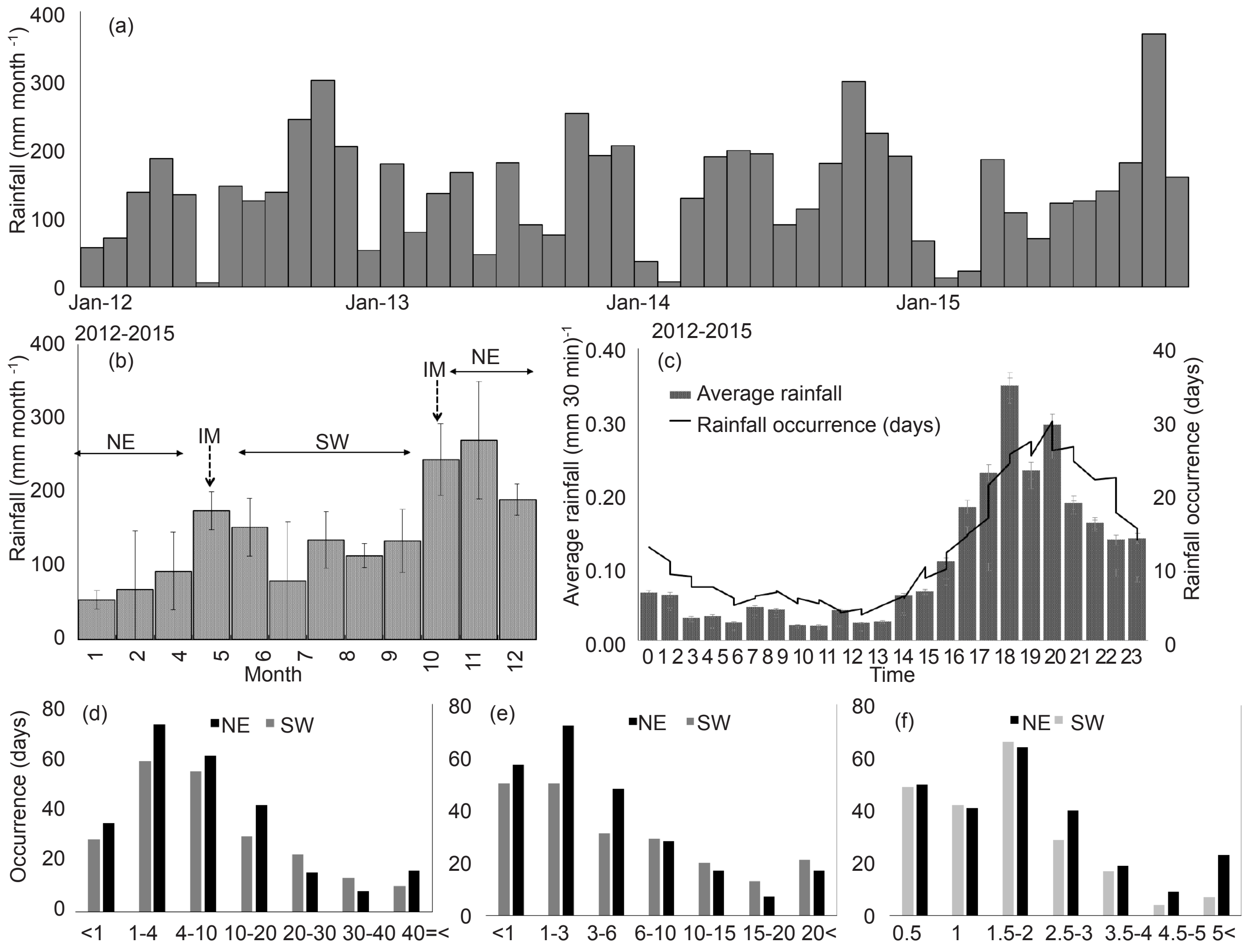

Figure 2 Rainfall characteristics in Pasoh FR in 2012–2015; (a) monthly amount of rainfall, (b) 4-year average and standard deviation of monthly rainfall; (c) 4-year average of rainfall amount and rainfall at 30-min intervals in one day, (d) distribution of daily rainfall amount (mm day^{-1}), (e) maximum rainfall intensity in 30 min (mm 30 min^{-1}) for each day and (f) rainfall duration (hours) for each day during the north-east (NE) and south-west (SW) monsoon seasons; each monsoon season was 4 months long; IM = intermonsoon

SW monsoon were -5.60 ± 2.75 and -32.7 ± 22.0‰ respectively and were slightly greater during the SW monsoon than during the NE monsoon season ($\delta^{18}O$ = -6.32 ± 3.36‰ and δ^2H = -39.7 ± 26.3‰). No differences were detected between monsoon seasons.

The relationships between δ^2H and $\delta^{18}O$, defined as the Local Meteoric Water Line (LMWL), were δ^2H (‰) = 7.9 $\delta^{18}O$ (‰) + 11.6 (r^2 = 0.98) for SW monsoon season and 7.8 $\delta^{18}O$ (‰) + 9.3 (r^2 = 0.99) for NE monsoon season (Figure 3). The intercept d (deuterium excess) value was slightly lower during the NE monsoon season than during the SW monsoon season. Both values fit the GMWL well (r^2 = 0.98). Generally, the regression lines between the NE and SW seasons including all data points were indistinguishable.

Comparison of long-term average monthly isotope signal with values from GNIP stations in neighbouring countries

The long-term monthly mean rainwater $\delta^{18}O$, δ^2H and deuterium excess values and monthly rainfall amount at Pasoh FR (Figure 4 and Table 2) had similar bimodal rainfall pattern to those at Kuala Lumpur and Singapore, but received less rainfall at the beginning of the year compared with the other two stations. Rainfall isotope patterns at Pasoh FR were also bimodal. Pasoh FR showed more positive isotope values during months with less rainfall. Cameron Highlands, located at high altitude, showed more negative isotope values. Kota Bahru, located on the east coast of Peninsular Malaysia, showed less negative isotope values compared with Pasoh FR with

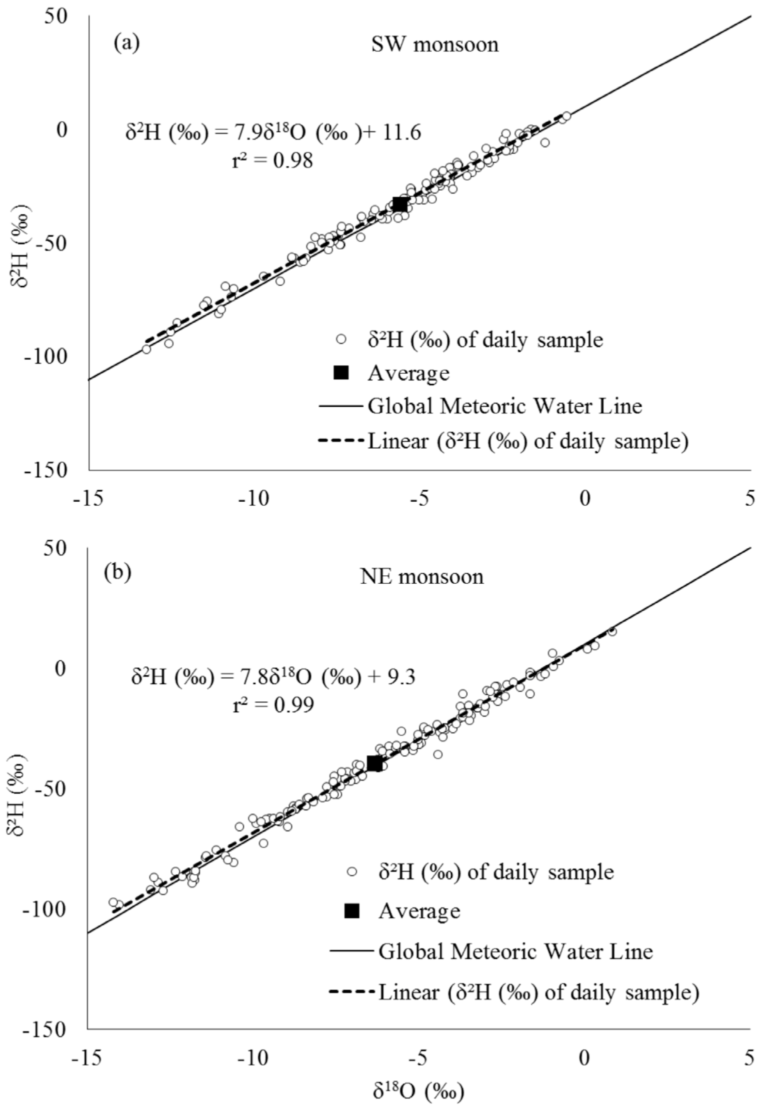

Figure 3 Relationship between δ^2H and $\delta^{18}O$ in daily rainfall samples fitted with the local linear regression line and Global Meteoric Water Line, SW = south-west, NE = north-east

Table 2 Long-term monthly rainfall amount and long-term monthly average rainwater δ18O, δ2H and deuterium excess

Month	Rainfall			δ18O(‰)			δ2H(‰)			Deuterium excess		
	Average	SD	n	Average	SD	n	Average	SD	n	Average	SD	n
Jan	53.76	12.26	4	-5.08	3.32	3	-31.3	26.5	3	9.3	3.2	3
Feb	67.79	79.43	4	-2.73	3.37	3	-12.1	24.8	3	9.8	2.9	3
Mar	92.54	52.61	4	-3.11	1.57	3	-15.	12.6	3	9.6	2.5	3
Apr	174.31	25.59	4	-4.85	1.88	3	-26.6	14.2	3	12.	3.1	3
May	151.98	39.00	4	-6.98	2.06	3	-43.7	15.8	3	12.2	2.1	3
Jun	79.26	80.63	4	-4.40	1.80	3	-23.8	15.6	3	11.4	3.2	3
July	135.13	38.11	4	-3.81	1.92	3	-17.6	14.0	3	12.9	2.6	3
Aug	113.55	16.21	4	-5.17	2.42	3	-28.2	18.1	3	13.2	2.8	3
Sept	133.18	42.76	4	-5.64	2.05	4	-33.9	16.9	4	11.3	2.9	4
Oct	243.65	48.48	4	-5.34	2.14	4	-30.2	17.4	4	12.6	2.7	4
Nov	270.26	79.32	4	-8.02	2.36	4	-51.7	18.7	4	12.4	2.4	4
Dec	189.73	21.30	4	-6.36	2.93	4	-40.5	22.9	4	10.4	2.6	4

SD = standard deviation

heavier rainfall during the NE monsoon season (Figures 4m and n). Alor Setar and Langkawi showed isotope patterns similar to those of Bangkok, which were unimodal in shape and decreased in September and October.

Most of the sites had comparable relationships between long-term mean rainfall and isotope values (Figure 4). The slope of the relationship between isotope values and monthly rainfall was steep and similar to that reported for maritime continents (Kurita et al. 2009). By contrast, isotopes at the Cameron Highlands station were more negative than those at the other sites. Kota Bahru during the NE monsoon season and Langkawi during the SW monsoon season showed less negative isotope values under heavy rainfall conditions.

Daily and seasonal variation in isotopes in precipitation

A time series of rainwater δ18O, δ2H and deuterium excess in the daily rainfall samples and the 30-day running average from September 2012 to December 2015 are shown in Figures 5a–c to examine the detailed daily and seasonal variation in the isotopes in precipitation at Pasoh FR. The isotope values varied considerably during the day, seasons and between years. The δ18O and δ2H values decreased during monsoon onset in May (SW) and November (NE) but this tendency was mitigated compared with the long-term mean monthly trend. The isotope values tended to be lower during the middle of the rainy season compared with those in the beginning of the rainy and drier seasons, and the pattern of dry and wet seasons differed between years. Deuterium excess increased with decrease in δ18O and δ2H. The relationship between monthly average over 4 years and isotope values is shown in Figures 5d and e. The δ18O and δ2H values showed the amount effect during the NE monsoon seasons but were scattered during the SW monsoon season and especially during the intermonsoon season.

Both δ18O and δ2H were significantly related to daily rainfall amount (r = -0.218 to -0.391), maximum rainfall intensity (r = -0.206 to –0.386) and duration (r = -0.247 to -0.333) for both monsoon seasons ($p < 0.05$) (Figures 6a–f). However, the relationships included considerable scatter. The larger deuterium excess values were not detected during small rain events, small maximum rainfall intensity and short-duration rainfalls (Figures 6g–i), although they were occasionally observed during larger scale rain events. No clear differences were detected between the seasons, although values were slightly lower during the NE monsoon season because more data fell within the high rainfall range.

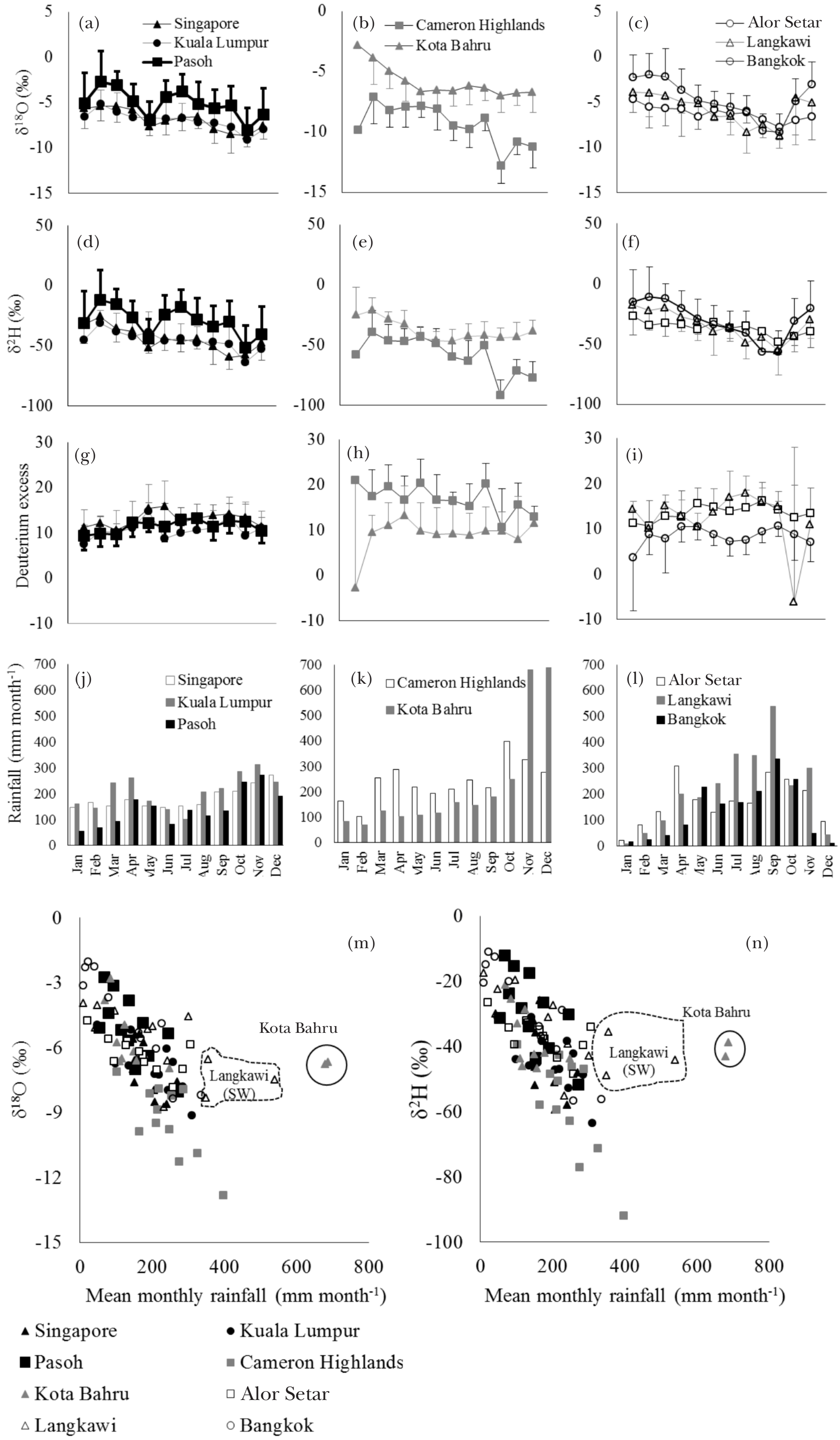

Figure 4 Long-term monthly average rainwater (a–c) $\delta^{18}O$, (d–f) $\delta^{2}H$, (g–i) deuterium excess, (j–l) monthly rainfall amount, and relationship between monthly rainfall amount and (m) $\delta^{18}O$ and (n) $\delta^{2}H$ at Pasoh FR and nearby Global Network of Isotopes in Precipitation stations; error bars show standard deviations, long-term monthly values for Pasoh FR were calculated based on monthly statistics for 3 or 4 years (n = 3 or 4)

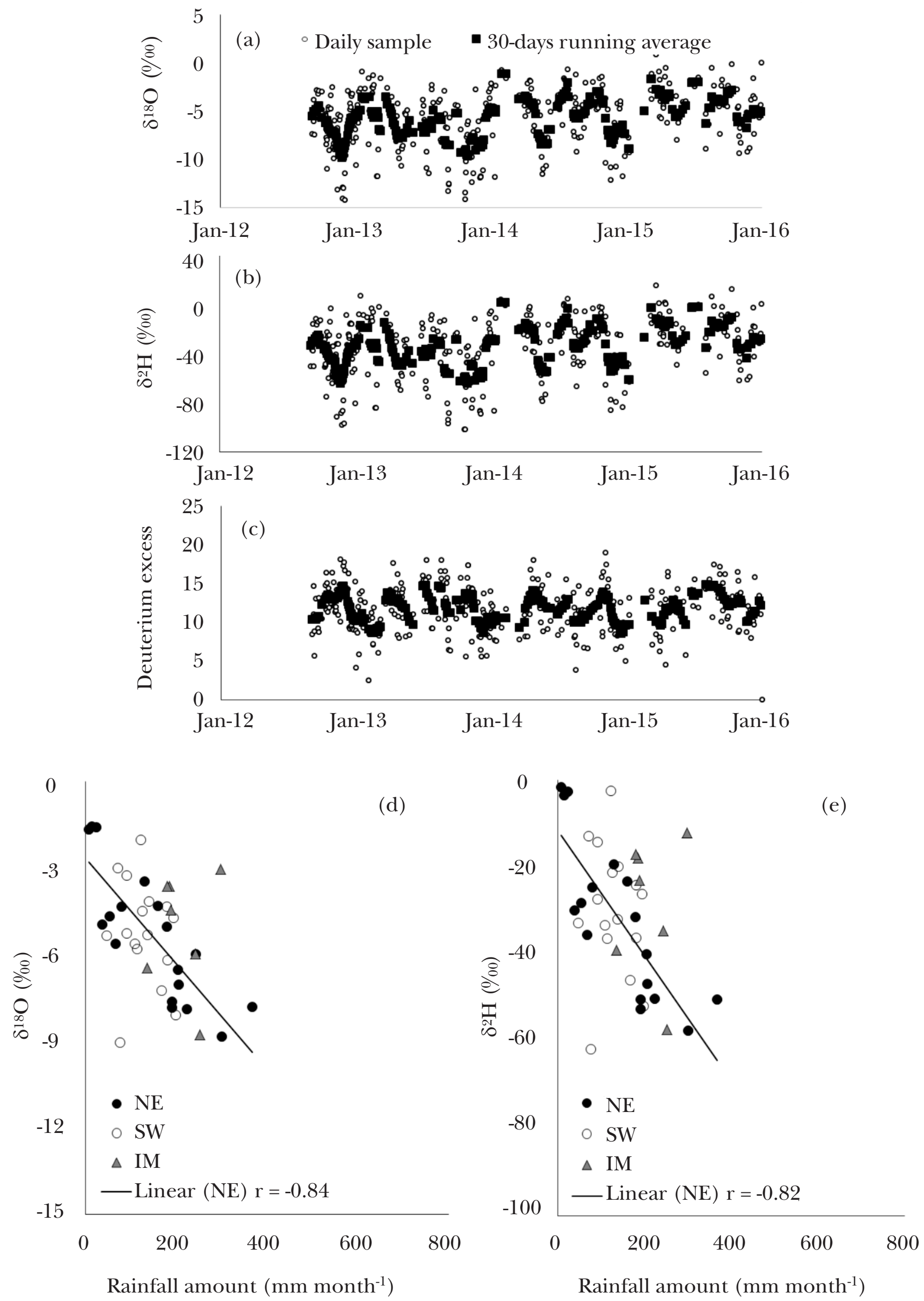

Figure 5 Time series of rainwater (a) $\delta^{18}O$, (b) $\delta^{2}H$, and (c) deuterium excess in daily rainfall samples with 30-day running average, and the comparison between monthly rainfall amount and monthly average of rainwater (d) $\delta^{18}O$ and (e) $\delta^{2}H$ at Pasoh FR from September 2012 till December 2015; lines in (d) and (e) show linear regressions for the relationship between $\delta^{18}O$ and monthly rainfall amount during the north-east (NE) monsoon season; SW = South-west; IM = intermonsoon

Figure 7a and b show a comparison of $\delta^{18}O$ values with amounts of daily rainfall and the API60, which was calculated as cumulative rainfall and used as a wetness index for this study. In this analysis, we did not divide the data into seasons. We detected significant correlations for amount of rainfall and AP160. However, the correlation was stronger with the latter ($r = -0.44$, $p < 0.001$) than with the amount of rainfall each day ($r = -0.30$, $p < 0.001$). The seasonal trend in $\delta^{18}O$ can be produced by using the relationship between the 30-day running average of $\delta^{18}O$ and the 30-day running average of API60 (Figure 7c, $r = -0.49$, $p < 0.001$).

DISCUSSION

Rainfall characteristics

The rainfall characteristics in Pasoh FR generally corresponded to typical weather in Peninsular Malaysia, which is characterised by two monsoon regimes (Figure 2a and b). This condition results in a bimodal rainfall pattern on the west coast and a unimodal rainfall on the east coast (Suhaila & Abdul Aziz 2009). Most rain fell in the Pasoh FR during the late afternoon to midnight and was intense and of short duration (Figure 2e and f), indicating that precipitation at the study site was mainly caused by a convective process.

Distribution of isotope values in precipitation

Our results showed no difference in the distribution of isotope values in precipitation between the NE and SW monsoon seasons (Figure 3). The best fit equation for the GMWL is $\delta^2H = 8 \times \delta^{18}O + 10$, as reported by Dansgaard in 1964. Similar result with other areas within the tropical region means that the precision of data in this study is high and acceptable. Thus, data from Pasoh FR can be used for studies of forest water use estimation, water quality and tracing water source. The value of 10 is an offset known as deuterium excess under the condition that the slope of the line is fixed at 8. The global average is 10 but varies according to local conditions known as the LMWL. The LMWL approximates the $\delta^{18}O$ and δ^2H values at a local scale and the slope value varies with local isotope values. Increases in deuterium excess of rainwater originate from re-evaporated moisture from continental basins and moving of water vapour (Kondoh & Shimada 1997). The relationship between $\delta^{18}O$ and δ^2H at Pasoh FR was defined as $\delta^2H = 7.9\ \delta^{18}O + 11.6$ (SW monsoon) and $\delta^2H = 7.9\ \delta^{18}O + 9.0$ (NE monsoon), which is similar to that in Borneo, which has been defined as $\delta^2H = 7.9\ \delta^{18}O + 10.3$ (Moerman et al. 2013). The slope was close to 8, which was near equilibrium. The slope for Pasoh FR was very similar to several continental stations in Indonesia, although other Indonesian stations located near the coast and small islands showed slopes near 7 (Rozanski et al. 1993, Clark & Fritz 1997, Belgaman et al. 2016). With a slope near 8, Pasoh FR corresponded to the theoretical results obtained under isotopic equilibrium conditions (Belgaman et al. 2016).

Comparison of long-term average monthly isotope signals with the nearby GNIP stations

Pasoh FR showed a seasonal trend in isotope values similar to those in Kuala Lumpur and Singapore, but different from those at the northern Peninsular Malaysia stations, mainly due to the different rainfall patterns (Figure 4). Rainfall pattern for most of the east coast of Peninsular Malaysia is unimodal, in which extreme rainfall occurs during particular months of the NE monsoon season (Suhaila et al. 2010). In Cameron Highlands (1430 m above sea level), the relationship between isotope values and rainfall is influenced by altitude effect (Dansgaard 1964). The different seasonal rainfall trends in Langkawi, Alor Setar and Bangkok could be associated with the different seasonal isotope patterns (Figure 4).

The slope for the relationship between long-term average of monthly $\delta^{18}O$ and monthly rainfall was steeper in the maritime continental region of Indonesia than in marine subtropical island stations, namely, Palau and Bali (Kurita et al. 2009). The authors reported that lower $\delta^{18}O$ values during the rainy season could not be explained by the local rainout effect because the intensity of atmospheric convergence during the rainy season was similar in the two region. The factor underlying this situation is the spatial distribution of vapour during the movement of moisture from adjacent regions. The slopes obtained at Pasoh FR and the nearby GNIP stations in Peninsular Malaysia were also rather steep and similar to those at maritime continental stations in Indonesia (Kurita et al. 2009), except for Kota Bahru during the NE monsoon season and Langkawi during the SW monsoon season (Figures 4m and n). We excluded the amount effects of Cameron Highlands from the slope analysis as this site might be influenced by the altitude effect. At Kota Bahru, which is located on the east coast of Peninsular Malaysia, the slope was less steep during extreme (> 600 mm month^{-1}) rainfalls in November and December. Langkawi, an island located on the west coast of Peninsular Malaysia, also experienced similar trend during the SW monsoon season (Figure 4m and n). These results suggested that the rest of the sites, which had steeper slopes similar to those found by Kurita et al. (2009), could be affected by distillation during land transport from source regions.

Daily and seasonal variation in isotopes in precipitation

The daily isotope values and rainfall characteristics were significantly correlated (Figures 5 and 6), but the correlation coefficients were considerably scattered. Post-condensation process considerably influenced the amount effect on a short timescale (Moerman et al. 2013). Intense rainfall in the tropics, mainly result of convective air mass, depletes isotopes in precipitation (Cole et al. 1999). Although the relationship between isotopes and rainfall characteristics are often not strongly correlated at a shorter timescale, amount effects may still be observed (Risi et al. 2008, Kurita et al. 2009). Rainwater isotopes at Pasoh FR were significantly related to the daily-scale local rainfall (Figures 6a–f). We examined the relationship between detailed rainfall characteristics, such as rainfall intensity and duration but did not detect any stronger correlations between these parameters and isotopes compared with daily rainfall amount. This may have occurred because our study site is characterised by a typical rainfall pattern with high intensity and short duration, which varied little. We assumed that rainwater isotopes in a small rain event caused by small-scale local convection may be influenced by land-originating re-evaporated moisture, and that this was one of the reasons why the isotopes varied on a daily timescale. However, we did not detect any increase in deuterium excess in such rainwater. Rather, smaller deuterium excess values were detected for smaller-scale rainfall events (Figures 6g–i). This suggested that scatters of isotope values in small rain events were not the main result of adding re-evaporated moisture from the land surface. It also suggested that land was not the major determining factor for the variability of isotopes in this area.

The amount effect on a longer timescale may be associated with large-scale atmospheric conditions such as movement of the Inter-Tropical Convergence Zone (Kurita et al. 2009). The isotope values in precipitation during the rainy season were lower than those during the dry season. Therefore, a negative correlation was observed between rainfall and the isotope values. Distillation during land transport of water vapour caused low isotope values in precipitation (Kurita et al. 2009). The combination of continental and amount effects may contribute to the complexity of seasonal rainfall isotope values, which leads to relatively high rainfall isotope values in February–April and August–October (shoulder seasons). The bimodal seasonal pattern and amount effect at Pasoh FR became clearer in the long-term average monthly data (Figures 4–6). Variation in isotope signals was more closely correlated with the 60-day antecedent rainfall index than with the amount of rainfall each day (Figures 7a and b), so we were able to roughly reproduce the seasonal trend in $\delta^{18}O$ using the antecedent rainfall index (Figure 7c). Results for Pasoh FR also suggested that the effects of rainfall amount on isotope composition at the study site resulted from the degree of rainout on a larger scale, including upstream transport pathways of water vapour, antecedent conditions and local-scale and specific rain events.

CONCLUSIONS

Most of the rain events at Pasoh FR were characterised as convective rainfall and no differences in rainfall characteristics and isotope signature were detected between the SW and NE monsoon seasons. Pasoh FR showed similar seasonal trend in isotope values compared with trends nearby GNIP stations such as Kuala Lumpur and Singapore, while differing from those at stations in northern Peninsular Malaysia, which was mainly due to the different rainfall patterns. The amount effect was clearly detected and comparable with those of the nearby GNIP stations for the long-term mean monthly statistics, while it was obscured on the daily timescale and for the monthly rainfall not averaged over the long-term. The daily isotope values at Pasoh FR were negatively correlated with rainfall amount, maximum rainfall intensity and duration but the correlation coefficients were small. As we did not detect any increase in the deuterium excess in such rainwater, the scatter in the isotope values from small rain events did not mainly result from adding re-evaporated moisture from the land surface. Seasonal isotope values were more closely correlated with the 60-day antecedent rainfall index than with the amount of rainfall each day. Overall, our results strongly suggested that rainfall amount effects of isotope composition at the study site resulted from the degree of rainout on a larger scale, including upstream and antecedent conditions, in addition

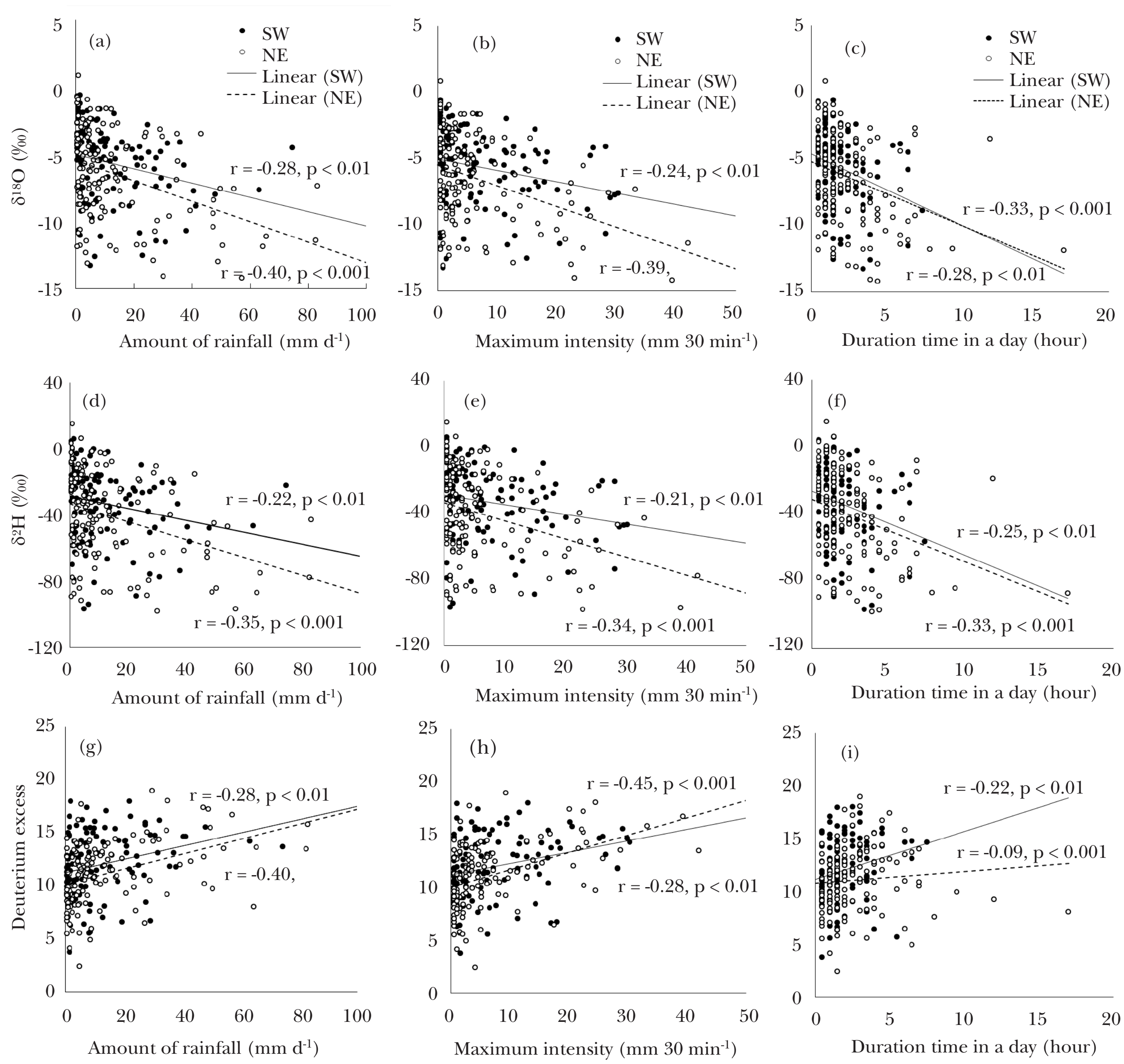

Figure 6 Comparison between (a–c) $\delta^{18}O$, (d–f) $\delta^{2}H$ and (g–i) deuterium excess and daily rainfall amount (mm day^{-1}); maximum rainfall intensity per 30 min (mm 30 min^{-1}) for each day; and rainfall duration (hours) for each day during the north-east (NE) and south-west (SW) monsoon seasons

to that on a local scale and on specific rain events. These results will be useful to understand the mechanisms for the variability in rainfall isotope signals in Malaysian tropical rainforests and improving climate change forecasts. The availability of rainwater isotope data serves as fundamental information for forestry research and management. This result becomes very useful when paired up with isotope in xylem and soil water, evapotranspiration and soil water content for the estimation of forest water use.

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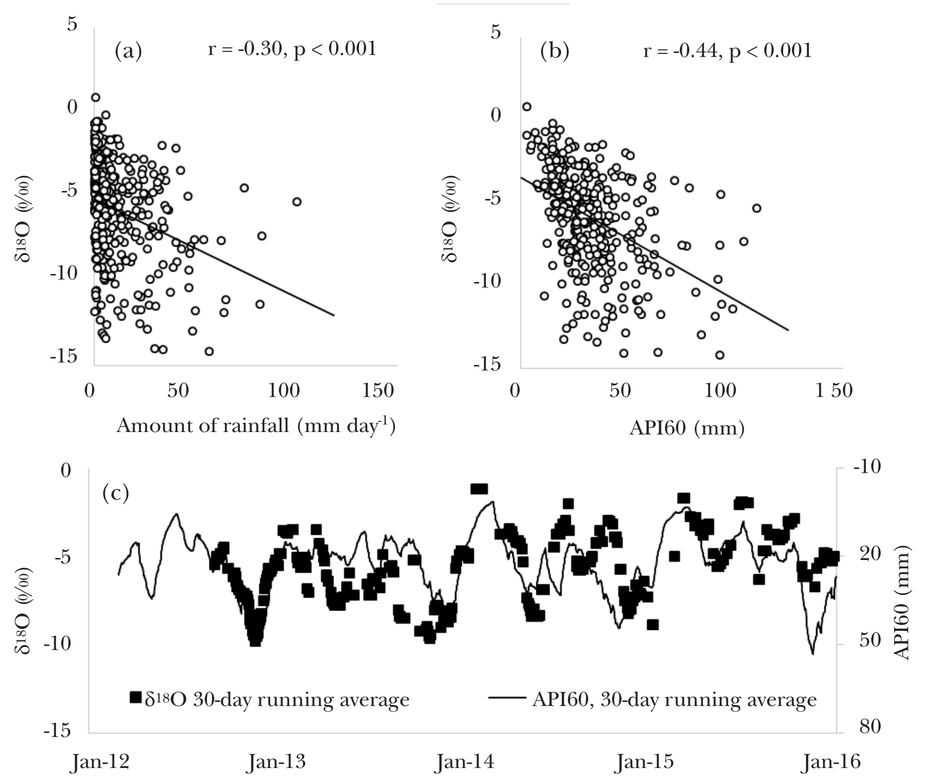

Figure 7 Comparison between $\delta^{18}O$ and (a) daily rainfall amount (mm day^{-1}) and (b) the 60-day antecedent precipitation index (API60); lines show linear regressions; (c) the 30-day running average of daily $\delta^{18}O$ and API60 from September 2012 till December 2015

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