LONG-TERM VARIATION IN SOIL MOISTURE IN PASOH FOREST RESERVE, A LOWLAND TROPICAL RAINFOREST IN MALAYSIA

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NOGUCHI S, KOSUGI Y, TAKANASHI S, TANI M, NIIYAMA K, SITI AISAH S & LION M. 2016. Long-term variation in soil moisture in Pasoh Forest Reserve, a lowland tropical rain forest in Malaysia. Clarifying variations in soil moisture is an important part of hydrological and ecological studies in tropical rainforests. Volumetric soil water content (VSWC) was measured at depths of 10, 20 and 30 cm at Pasoh Forest Reserve (PFR) in Peninsular Malaysia for 12 years. VSWC ranged from 0.280–0.442 $m^3 m^{-3}$ (mean ± standard error; 0.373 ± 0.001 $m^3 m^{-3}$) and was affected not only by the south-west and north-east monsoons but also by El Niño and La Niña events. Mean VSWC was high during La Niña events and low during El Niño events. In a normal El Niño/Southern Oscillation (ENSO) phase, VSWC showed both low and high conditions. An antecedent precipitation index (API) was calculated using 20 years of rainfall data. API_{90} ranged from 1.2–257.3 mm (25.4 ± 0.2 mm). The variations in API_{90} followed a similar pattern to variations in the VSWC. API_{90} can be used to estimate soil moisture conditions as a drought indicator. An API_{90} of less than 10 mm lasted more than 14 successive days during the normal ENSO phases when five mass flowerings occurred at PFR from 1995–2014.

Keywords: Antecedent precipitation index, El Niño, La Niña, mass flowering, normal ENSO phase, Peninsular Malaysia, south-west monsoon, north-east monsoon

INTRODUCTION

Tropical rain forests play important roles in the maintenance of the global environment. In Peninsular Malaysia, tropical forest research has been actively conducted since 1961 at Pasoh Forest Reserve (PFR). PFR is recognised under UNESCO's International Biological Programme (IBP) for its importance as an international research site for ecological studies. Many studies related to tropical forest biology and ecology have been conducted in PFR (e.g. Kochummen et al. 1990, Condit et al. 2000, Manokaran et al. 2003, Niiyama et al. 2010). The construction of a meteorological observation tower with a canopy walkway in 1992 facilitated many microclimatological studies, including those studies related to energy exchange and surface conductance (Tani et al. 2003a), evapotranspiration (Tani et al. 2003b, Kosugi et al. 2012), transpiration (Takanashi et al. 2003), rainfall characteristics (Noguchi et al. 2003) and the spatial distribution of throughfall (Konishi et al. 2006).

Variations in soil moisture affect hydrological processes such as evapotranspiration, the response runoff to rainfall as well as the transport of water and solutes in soils. An improved understanding of variation in soil moisture is important when evaluating the hydrological processes in the tropical rainforest. Elucidating soil moisture variability is also important for scientists attempting to understand tree physiology in tropical rainforests. Droughts may be one of several environmental cues that trigger the phenomenon of mass flowering at irregular intervals in these forests (Numata et al. 2003). However, owing to very limited soil moisture observations, these droughts were identified based on rainfall data, which is more readily available (Numata et al. 2003). While rainfall data can be used to model drought, including other contributing variables such as soil moisture can improve accuracy (Sheffield et al. 2004). Determining the variations in soil moisture based on long-term data is therefore an important ecological subject in tropical rainforest research. The present study has four main objectives based on long-term soil moisture and rainfall data in PFR: to 1) to understand the variation in soil moisture of a tropical rain forest, (2) examine the differences between El Niño and La Niña events, in terms of soil moisture variability, (3) evaluate the relationship between rainfall and soil moisture using an index and (4) discuss soil moisture conditions during mass flowering.

MATERIALS AND METHODS

Site description

Pasoh Forest Reserve (2°59' N, 102°19' E; Figures 1 and 2a) is located in Negeri Sembilan, Peninsular Malaysia. Primary lowland mixed dipterocarp forest covers the core area (600 ha) of the reserve (2450 ha) and consists of various species of *Shorea* and *Dipterocarpus* (Manokaran et al. 1992). A 6-ha (200 m × 300 m) study area was established for long-term ecological research in 1994 (Niiyama et al. 2003). A 52-m high tower was erected in the 6-ha plot for meteorological observation (Figures 1 and 2c). Mean annual precipitation and temperature over 15 years (1997–2011) was 1833 mm and 25.4 °C respectively. The saturated hydraulic conductivity (Ks) decreased with increasing soil depth. The geometric mean of Ks ranged from 2.03×10^{-2} cm s^{-1} at 5 cm depth to 1.84×10^{-3} cm s^{-1} at 40 cm depth. The soil type around the tower near IBP Plot 1 is Haplic Acrisol according to the FAO Soil classification (Yamashita et al. 2003) and has thin organic (0–2 cm) and A (5–15 cm) horizons.

Measurements of rainfall and soil moisture content

Rainfall data were collected at 30-min intervals using a tipping-bucket rain gauge placed at the top of the tower above canopy level (Figure 2b) and a second gauge placed 430 m away in a clearing at the Pasoh Climate Station (Saifuddin et al. 1994). The amount of rainfall collected was calibrated by totalling the rain gauge data collected at the Pasoh Climate Station. Volumetric soil water content (VSMC) was measured using time domain reflectrometry (TDR) sensors at 0.1, 0.2 and 0.3 m depths at three points around the tower (Figure 2d). The data represented 20 years (1995–2014) for rainfall and 12 years (2003–2014) for VSMC.

Calibration of the TDR sensors

The TDR sensors were calibrated using the standard procedure for calibrating capacitance sensors outlined by Starr and Paltineanu (2002) as follows: (1) bulk soil to be measured with the TDR sensors was collected at 0.1–0.3 cm depth; (2) the soil was air-dried and large objects (e.g. large rocks) removed; (3) the soil was packed into an acrylic calibration container (width × depth × height: 120 mm × 330 mm × 95 mm) at approximately the field bulk density; (4) the mass of the soil and container was measured;

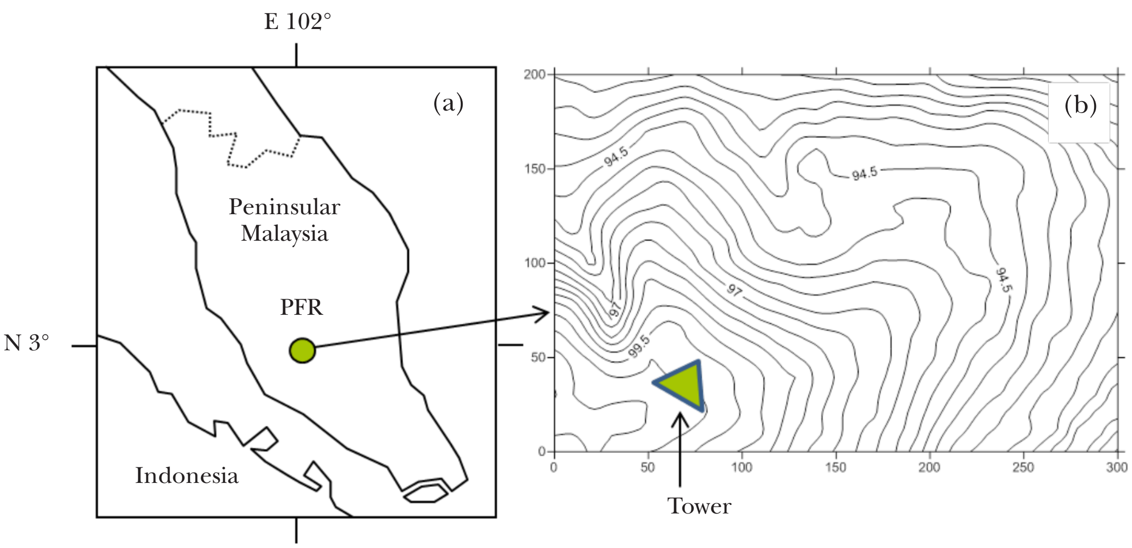

Figure 1 The study location in Peninsular Malaysia: (a) location of Pasoh Forest Reserve (PFR) and (b) location of the tower at the 6-ha research plot in PFR

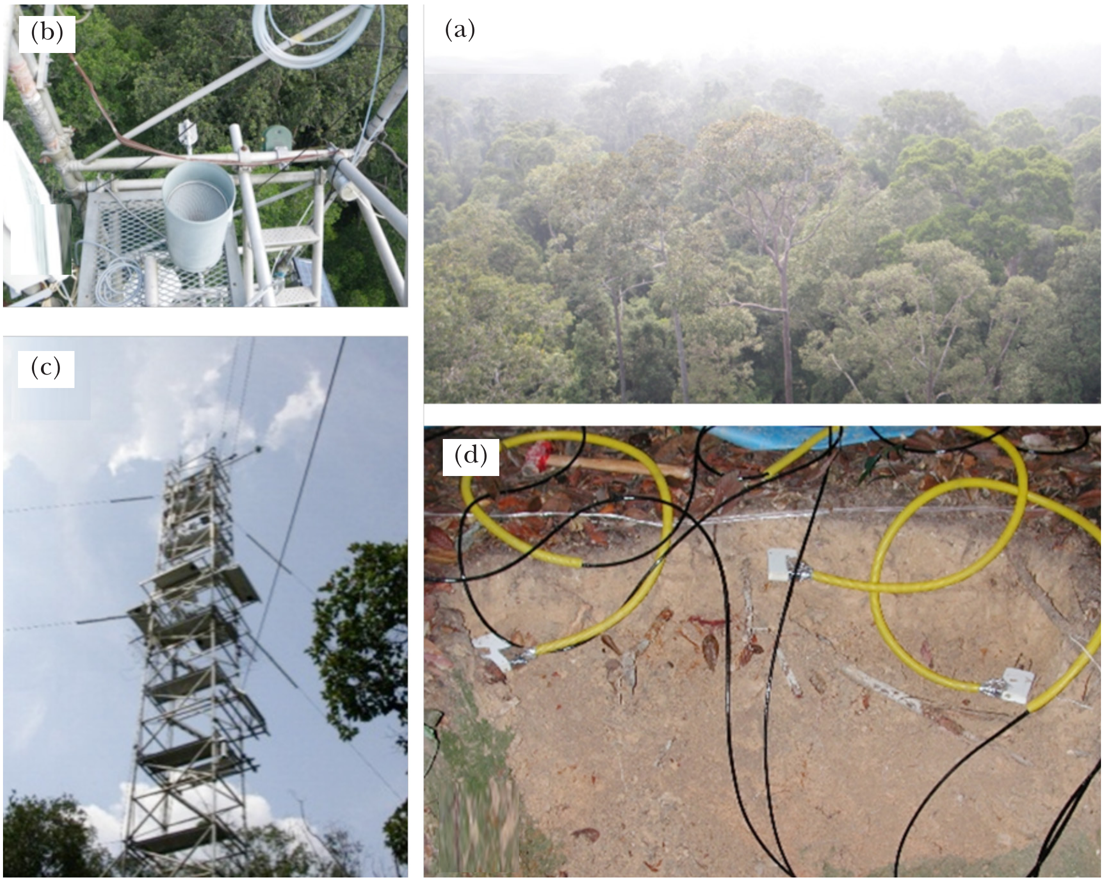

Figure 2 Photos depicting aspects of the study: (a) the lowland tropical forest at Pasoh Forest Reserve as viewed from the top of the tower, (b) the tipping-bucket rain gauge at the top of the tower, (c) the meteorological observation tower and (d) soil profile where time domain reflectometry sensors were installed at depths of 10, 20 and 30 cm

(5) the TDR sensor was inserted horizontally, directly into the full soil container and a sensor reading taken; (6) water was added to the soil as evenly as possible; (7) steps (4–6) were repented until the soil neared saturation. The bulk density of the sample was maintained throughout the calibration process by packing the same soil sample to the same level on the calibration container at each soil water content; (8) the volumetric soil samples were dried and weighed; (9) volumetric moisture valves obtained with the gravimetric method and with the use of TDR probes were calculated. The regression equations (1) and (2) are as follows:

$$y = 3.683x^3 - 4.958x^2 + 2.539x - 0.0117,\ x \leq 0.500,\ r^2 = 0.981 \quad (1)$$

$$y = 0.833x + 0.086,\ x > 0.500,\ r^2 = 0.986 \quad (2)$$

where x = VSWC ($m^3\ m^{-3}$) determined with the TDR method and y = VSWC ($m^3\ m^{-3}$) determined with the gravimetric method.

Definition of El Niño and La Niña events, and mass flowering

The Japan Meteorological Agency defines an El Niño event as a period during which the mean of sea surface temperature anomalies occur in El Niño 3 Region (5°N–5°S, 90°W–150°W) for 5 consecutive months and remain +0.5 °C or greater than the mean for at least 6 consecutive months. Similarly, with the same time and location guidelines, a La Niña event has sea surface temperatures that differ by -0.5 °C or more from the mean. Other periods lasting at least 6 consecutive months are defined as normal events (Figure 3).

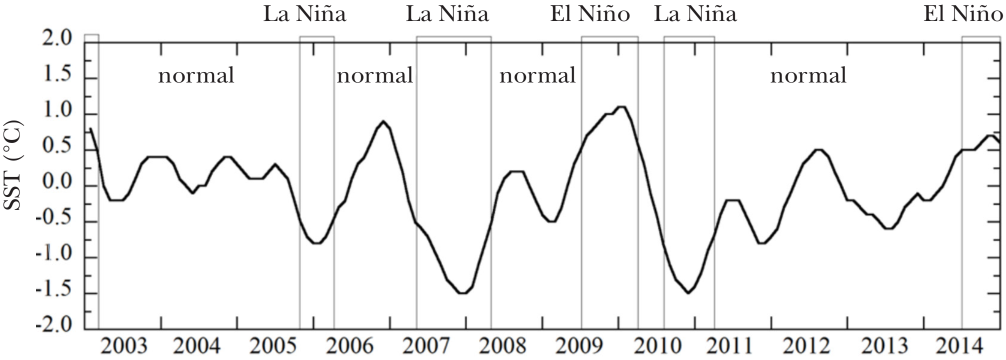

Figure 3 Five-month running means of sea surface temperature (SST) anomalies in El Niño 3 Region from 2003–2014 and classification of El Niño, La Niña and normal events; the El Niño 3 Region is bounded by 90°W–150°W and 5°S–5°N

Flowering events in PFR from 1980 to 2002 were classified as mass (major) and sporadic (minor) flowerings based on flowering densities of individual trees and species (Numata et al. 2003). From 1992, seed trap counts (Niiyama et al. 1999) provided additional data supporting the retrospective determination of the scale of these flowering events. High flower and seed counts recorded in 1996 and 2002, firmly established these as mass flowering event years. After 2002, the 1996 and 2002 flower and seed count data were employed as the baseline reference for classifying mass flowerings (K Niiyama, personal communication). Therefore, for the present study, we determined that the mass flowerings occurred in 1996, 2002, 2005, 2009 and 2014.

Analysis

Statistical analyses were performed to test the influence of El Niño, La Niña and normal events on soil moisture with analysis of variance (ANOVA) with Scheffe's post hoc test for multiple comparisons (Tsushima 2007). Trends in annual rainfall were evaluated using the non-parametric Mann–Kendall test, which has been widely used to test for randomness against trends in climatological time series (e.g. Kahya & Kalayci 2004). Statistical significance was set at $p < 0.05$. These analyses were conducted using SPSS software version 20 (2012) and the Igor Pro software version 6 (2007) programs.

An antecedent precipitation index (API_n) was used because API_n is the most widely used index for representing soil moisture conditions. API_n was defined as follows:

$$API_n = \sum_{i=1}^{n} P_i / i \quad (3)$$

where P_i is daily precipitation (mm) and i is the number of days beforehand (Mosley 1982). We tested 30, 45, 60, 75, 90 and 105 days as the value of n using equation (3) in the relationship between API and VSWC following Kosugi et al. (2007).

RESULTS

Annual and seasonal variations of rainfall and VSWC

The diurnal variation in VSWC and rainfall was synchronous (Figures 4a and b). Over the 12 years, VSWC ranged from 0.280–0.442 $m^3\ m^{-3}$ (mean ± SE; 0.373 ± 0.001 $m^3\ m^{-3}$). The lower and upper quartiles as well as the interquartile ranges of VSWC were 0.350, 0.397 and 0.047 $m^3\ m^{-3}$ respectively (Figure 4d). The minimum value was recorded on 26 February 2005 and the antecedent 49-day total rainfall was only 3.6 mm. VSWC on that day and 2 antecedent days were outliers. Yearly mean VSWC for 12 years ranged from 0.359 to 0.405 $m^3\ m^{-3}$ (0.373 ± 0.004 $m^3\ m^{-3}$; Figure 4c). The yearly mean VSWC increased with increasing annual rainfall when annual rainfall was more than 1600 mm $year^{-1}$ (Figure 4e).

Mean rainfall charted in 10-day periods, showed a distinct bimodal variation, i.e. two rainy seasons (Figure 5a). The peaks, which occurred at the end of March and end of October, appeared equal, but the latter peak was sustained through early December. Rainfall was lowest in early February and early August. Mean VSWC, graphed in 10-day periods, generally reflected that of mean rainfall, but fluctuations were not as large (Figure 5b). The two peak distributions suggest that the site was influenced by both the south-west and north-east monsoons (Figure 5c).

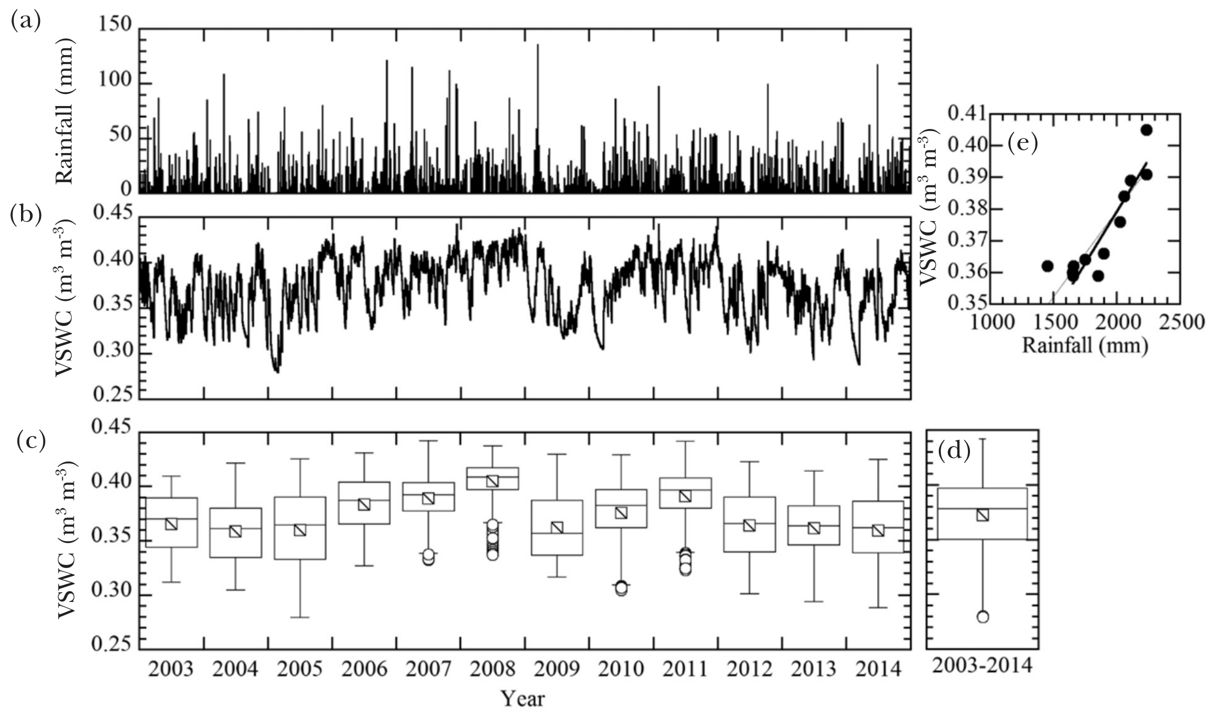

Figure 4 Summary statistics for rainfall and volumetric soil water content (VSWC) over 12 years (2003–2014) at Pasoh Forest Reserve: (a) daily variation in amount of rainfall, (b) daily variation in VSWC, (c) box plots of VSWC for each of the 12 years, (d) box plot of VSWC for the total study period and (e) relationship between yearly mean VSWC and annual rainfall

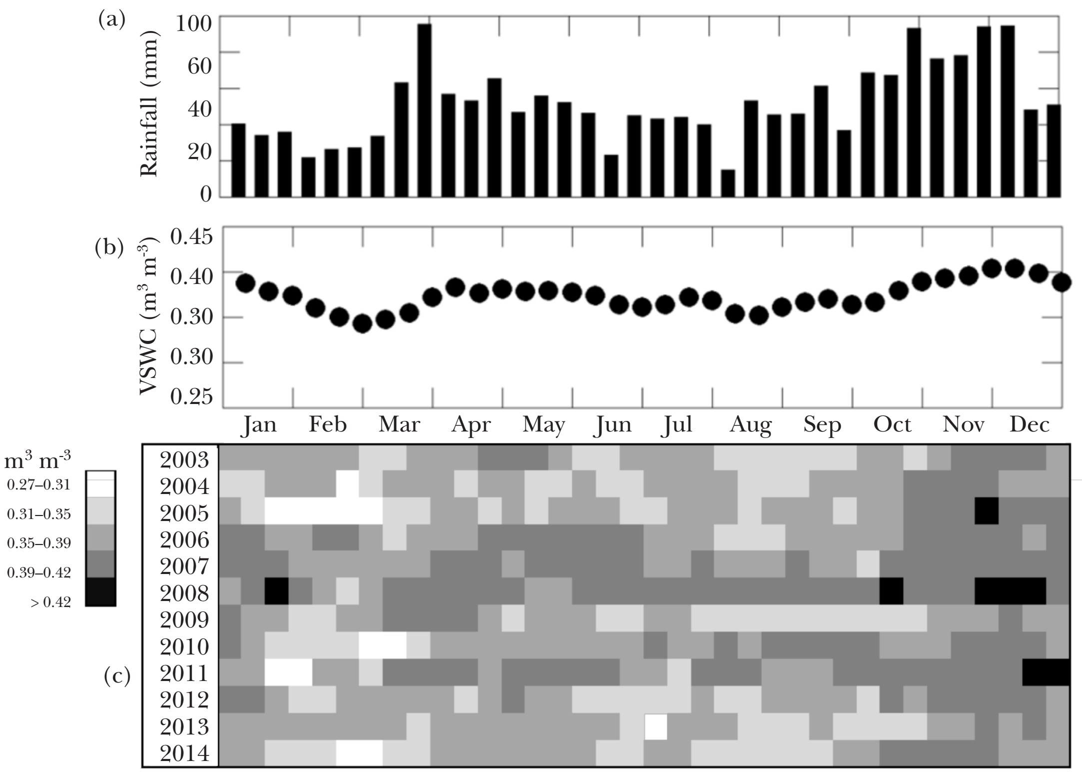

Figure 5 Seasonal variations in 10-day rainfall and volumetric soil water content (VSWC) over 12 years (2003–2014) at Pasoh Forest Reserve: (a) mean of total rainfall for each 10-day period, (b) mean of total VSWC for each 10-day period and (c) mean of total VSWC for each 10-day period of every year

Variation in soil moisture during El Niño, La Niña and normal events

The 12 years (2003–2014) of this study were divided into nine periods: two El Niños, three La Niñas and four normal events (Figure 3). Mean VSWC values for each period ranged from 0.347–0.398 $m^3 m^{-3}$, with the lowest value recorded during the first El Niño (June 2009–March 2010) and the highest value recorded during a normal event (May 2008–May 2009; Figure 6). Of note, the second to fourth largest values were recorded during La Niñas. In a normal ENSO phase, VSWC showed both low and high conditions. Extreme drying occurred in the normal phase.

All combinations of the nine periods analysed here were evaluated with Scheffe's post hoc test for multiple comparisons. No significant differences were observed among the following seven pairs of time periods with Scheffe's post hoc test: (1) October 2005–March 2006 vs April 2007–April 2008, p = 1.000; (2) October 2005–March 2006 vs May 2008–May 2009, p = 0.731; (3) October 2005–March 2006 vs July 2010–March 2011, p = 1.000; (4) April 2007–April 2008 vs May 2008–May 2009, p = 0.844; (5) April 2007–April 2008 vs July 2010–March 2011, p = 1.000; (6) May 2008–May 2009 vs July 2010–March 2011, p = 0.806 and (7) April 2011–May 2014 vs June 2014–December 2014, p = 1.000 (Figure 6). Significant differences were observed among twenty-nine pairs of the remainder.

Relationship between rainfall and an antecedent precipitation index (API) and variation in API

The relationships between API and VSWC when the value of n = 30, 45, 60, 75, 90 and 105 days are shown in Figure 7. The VSWC was shown as a logarithmic function of API value. The relationship was best when n = 90 (VSWC = 0.2929 ln (API) + 0.249, r^2 = 0.652). The nine years (1995–2003) of this study were divided into six periods: two El Niños, two La Niñas and two normal events (Figure 8a). API_{90} values ranged from 4.1–257.3 mm from July 1995 to December 2003 (Figure 8b). The API_{90} ranged from 1.2–257.3 mm (25.4 ± 0.2 mm) from June 1995 to December 2014. Mean API_{90} in the period was higher in La Niña events and lower in El Niño events. All combinations the six periods were evaluated with Scheffe's post hoc test for multiple comparisons. No significant differences were observed between the following pairs of time periods with Scheffe's post hoc test: (1) June 1995–February 1996 vs August 1998–April 2000, p = 0.936; (2) March 1996–March 1997 vs May 2000–May 2002, p = 0.658; (3) March 1996–March 1997 vs July 2002–February 2003, p = 1.000 and (4) May 2000–May 2002 vs July 2002–February 2003, p = 0.819 (Figure 8c). Significant differences were observed among eleven pairs of the remainder.

DISCUSSION

Measuring rainfall is easier than measuring soil moisture. API has been used to represent soil water condition when evaluating soil respiration (Kosugi et al. 2007) and stormflow generation (Negishi et al. 2007) in a tropical rain forest. The constant value n in equation (3) depended on environmental and soil factors such as shallow antecedent soil moisture, deep antecedent soil moisture and plant uptake of water. Negishi et al. (2007) used API to evaluate stormflow characteristics as an indicator of soil moisture

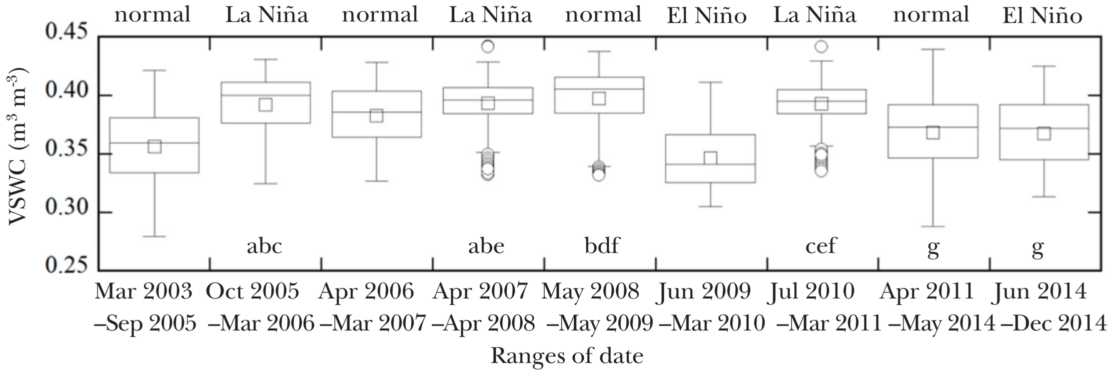

Figure 6 Box plots of volumetric soil water content (VSWC) during the El Niño, La Niña and normal events; box plots with the same letters indicate no statistical differences among the groups, significant differences were observed among twenty-nine pairs of the remainder

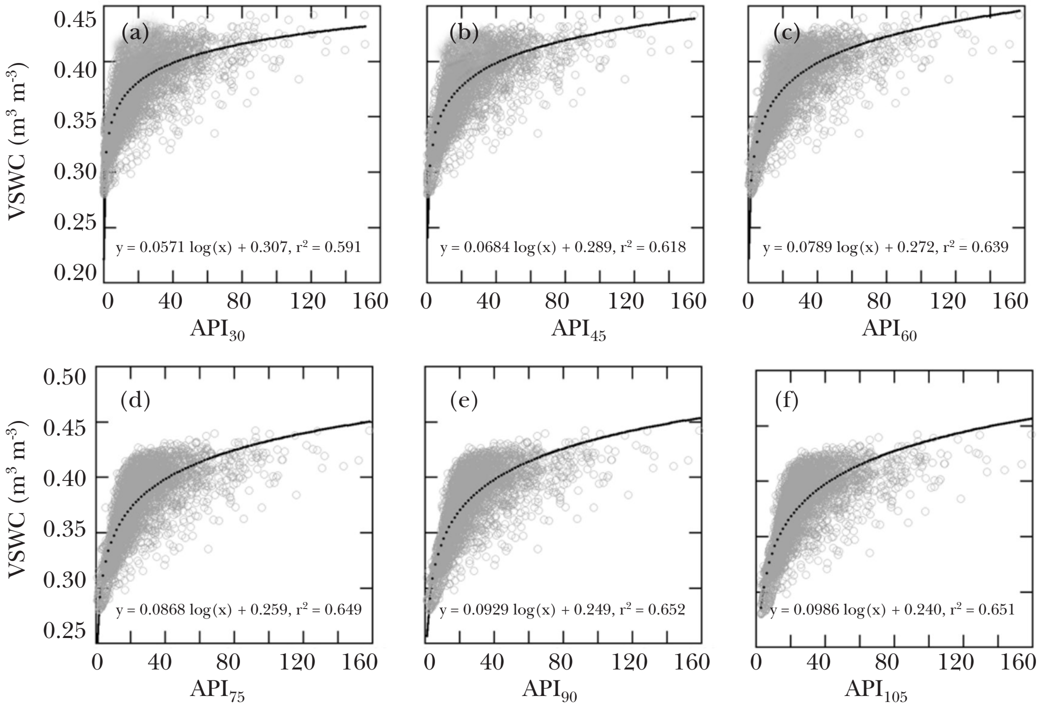

Figure 7 Relationship between the antecedent precipitation index (API) and volumetric soil water content (VSWC) when n is (a) 30, (b) 45, (c) 60, (d) 75, (e) 90 and (f) 105

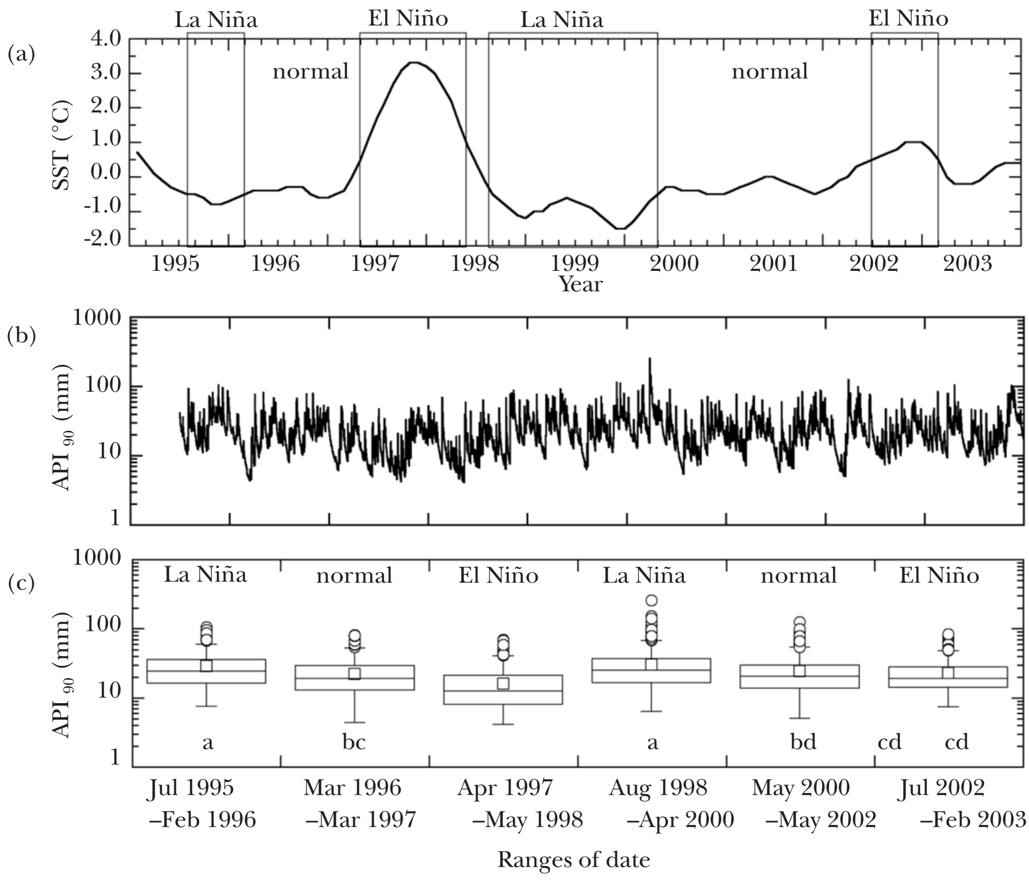

Figure 8 El Niño, La Niña and normal events and API_{90} variation from 1995–2003: (a) five-month running means of sea surface temperature (SST) anomalies in El Niño 3 Region and classification of El Niño, La Niña and normal events, (b) API_{90} variation and (c) box plots of API_{90} during El Niño, La Niña and normal events; box plots with the same letters indicate no statistical differences among the groups, significant differences were observed among 11 pairs of the remainder

conditions. However, Kosugi et al. (2007) tested 10, 30, 45, 60 and 75 days as the n values in the relationship with soil water content. Both cases are different. We also tested 30, 45, 60, 75, 90 and 105 days as the value of n in the present study. When the value of n was small (e.g. n = 30 or 45), r^2 was also small compared with that when the n was large (e.g. n ≥ 60). This occurred because there were 2354 days with no rain recorded over 12 years (53.7%) and the frequency at which API values approach 0 increases. The best value of n in this study was higher (i.e. n = 90; Figure 7) than the n = 60 reported by Kosugi et al. (2007). This occurred because the data set used in the present study was different than that used by Kosugi et al. (2007). Variation in API was positively correlated with that in VSWC, suggesting that API might be useful for estimating soil moisture in tropical rain forests where VSWC was not measured.

The results of the analysis of API_{90} during the El Niño, La Niña and normal events from 1995–2003 (Figure 8c) are in agreement with the results of the analysis of VSWC during the El Niño, La Niña and normal events from 2003–2014 (Figure 4c). The long-term observations of rainfall that are carried out in all of Malaysia (e.g. Wong et al. 2009) present possibilities of using API to evaluate soil moisture conditions over the long term.

At least 12 flowering events were observed at the PFR from 1976 to 2002 (Numata et al. 2004). We have focused on the variation in API_{90} when five mass flowerings occurred at PFR since 1995, all during March and in 1996, 2002, 2005, 2009 and 2014. API_{90} remained below 10 mm for more than 14 days in succession during the normal phases when these mass flowerings occurred (Table 1). This result suggested that both the south-west and north-east monsoons, instead of El Niño events, influenced mass flowering. Similar or drier conditions also occurred during other periods when mass flowering events did not occur (Table 1). Moreover, three mass flowering events occurred at PFR during La Niñas of 1976, 1985 and 1989 (Numata et al. 2004). An API_{90} of less than 10 mm has been recorded during La Niñas (Figure 8) over the past 20 years. We need longer-term monitoring data to clarify the variation of soil moisture during La Niña when mass flowering occurs.

Extreme drought affects tree species composition and diversity of tropical forests (Slik 2004). Studies of change in tropical forests highlight the potential importance of drought

Table 1 Periods when the antecedent precipitation index (API_{90}) stabilised, that is, was less than 10 mm and remained stable for more than 14 days

Date	Period (days)		Classification	API_{90} (mm)		Record of mass flowering event
				Range	Mean ± SE	
24 Feb–20 Mar 1996	26		Normal	4.4–9.8	6.1 ± 0.3	Numata et al. 2003
19 Jan–5 Feb 1997	18		Normal	6.2–9.6	8.0 ± 0.3	
19 May–8 June 1997	21		El Niño	5.0–9.2	6.7 ± 0.2	
11 Jul–27 Jul 2000	17		Normal	5.4–9.9	7.6 ± 0.3	
12 Feb–27 Feb 2002	16	26	Normal	5.1–9.9	7.1 ± 0.3	Numata et al. 2003
1 Mar–10 Mar 2002	10					
8 Aug–11 Sep 2004	35		Normal	4.1–9.7	6.6 ± 0.3	
21 Jan–27 Feb 2005	38		Normal	2.3–9.7	5.0 ± 0.3	Niiyama (personal communication)
3 Feb–16 Feb 2009	14		Normal	6.5–9.4	7.7 ± 0.2	Niiyama (personal communication)
19 Feb–21 Mar 2010	31		El Niño	2.9–9.4	5.0 ± 0.3	
13 Jul–27 Jul 2011	15		Normal	6.8–9.6	8.2 ± 0.2	
7 Jun–5 Jul 2012	29		Normal	5.9–9.9	7.6 ± 0.2	
27 Jan–9 Feb 2014	14	47	Normal	1.2–9.9	5.0 ± 0.4	Niiyama (personal communication)
12 Feb–16 Mar 2014	33					

SE = standard error

thresholds that could lead to substantial forest decline in the near future (Malhi & Philips 2004). Although mean annual rainfall for Peninsular Malaysia was ca. 2300 mm (Wong et al. 2009), the mean annual rainfall in PFR ranged from 1182 to 2235 mm (1817 ± 63 mm) over 20 years (1995–2014). PFR is located in an inland region with a lower mean annual rainfall than other parts of Peninsular Malaysia (Noguchi et al. 2003). On the other hand, annual evapotranspiration in PFR was 1287 ± 52 mm based on 7 years data (Kosugi et al. 2011). These results may explain why PFR is one of the most vulnerable regions for the tropical rain forest to changes in rainfall patterns. Trends in annual rainfall at PFR have increased ($\tau = 0.185$) but were not significant ($p = 0.255$) based on the non-parametric Mann–Kendall test. According to long-term meteorological data in Malaysia, the trends in mean surface temperature have increased but trend in rainfall was not clear. An evident upward trend of annual rainfall is simulated for the A1B scenario, but a downward trend is projected for both the A2 and B2 scenarios (Malaysian Meteorological Department 2009). Therefore, it is very important to continue to observe rainfall patterns to be able to clarify the effect of climate change on rainfall trend.

The mean rooting depth in a mixed dipterocarp forest was 2.35 m (Baillie & Mamit 1983). In PFR, Niiyama et al. (2010) reported that the maximum depth of tap roots was about 4 m while fine roots have also been found as deep as 4 m (T Yamashita, unpublished data). Seasonal variation in soil moisture at a depth of 160 cm reached a minimum about 20–30 days later than that at a depth of 10 cm (Noguchi et al. 1997). Soil moisture in the deeper layers, where the main root system was not found but was the source of transpiration, plays an important role in leaf flush during the dry season (Iida et al. 2015). Therefore, it is important to understand the variation in soil moisture deeper in the soil. Although the soil moisture of the upper 10–30 cm soil layer has been observed over the long term in PFR, little is known about the variation in soil moisture in such deep soil layers. We strongly underscore the importance of long-term monitoring of soil moisture including monitoring at deep depths for the elucidation of hydrological and ecological processes in tropical rain forests.

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