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ORIGINAL PAPER

Photosynthetically active radiation and comparison of methods for its estimation in equatorial Singapore

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Abstract Photosynthetically active radiation (PAR) is an important input variable for urban climate, crop modelling and ecosystem services studies. Despite its importance, only a few empirical studies have been conducted on PAR, its relationship to global solar radiation and sky conditions and its estimation in the tropics. We report in this study, the characterisation of PAR in Singapore through direct measurements and development of models for its estimation using input variables of global solar radiation (*H*), photometric radiation (*L*), clearness index (k_t) and sky view factor (SVF). Daily PAR showed a good correlation with daily *H* and had a comparatively small seasonal variation in PAR due to Singapore's equatorial position. The ratio of PAR to *H* (*PAR*/*H*) showed a slight depression in midyear from May to August, which correlated well with seasonal patterns in rainfall over the study period. Hourly *PAR*/*H* increased throughout the day. Three empirical models developed in this study were able to predict daily PAR satisfactorily, with the most accurate model being one which included both *H* and k_t as independent variables. A regression model for estimation of PAR under shaded conditions using SVF produced satisfactory estimation of daily PAR but was prone to high mean percentage error at low PAR levels.

1 Introduction

Photosynthetically active radiation, usually defined as solar radiation between 400 and 700 nm (Monteith 1972; Ross and Sulev 2000), is an important component of solar radiation for natural and urban ecosystems because it provides plants with almost all of its chemical energy needs (Givnish 1988). PAR is therefore a key determinant of primary productivity of natural ecosystems and crop production (Mercado et al. 2009; Monteith 1972). Through its control over primary plant processes such as stomatal regulation of photosynthesis and transpiration (Waring and Landsberg 2011), it also affects global water and carbon balance (Hetherington and Woodward 2003) and the global climate. In urban ecosystems, it influences urban energy, water and carbon balances through its effects on plant–environmental interactions in urban green spaces (Cleugh and Grimmond 2012). PAR is thus an important input variable in numerous ecophysiological and climate models, such as in Arora (2003), De Bruijn et al. (2014), Duursma and Medlyn (2012) and Mercado et al. (2007). It is also widely used in remote sensing methods for estimation of gross primary productivity (Schlesinger and Bernhardt 2013). Recent studies on the spatial distribution of PAR in urban areas also suggest that a better understanding of PAR is important to improve the ecological design and provision of urban green spaces to increase the environmental benefits or ecosystem services provided by urban greenery (Tan and Ismail 2014; Tan PY and Ismail MRB (Under Review, The effects of urban forms on photosynthetically active radiation and urban greenery in a compact city, Urban Ecosystems). Accurate estimation of PAR is understandably crucial for the efficacy of such studies, as uncertainties in estimation of PAR can lead to measurable differences in the predictions by ecophysiological models (Cho et al. 2010) and significantly affect the estimation of global primary productivity (Cai et al. 2014; Ito and Sasai 2006).

Despite its importance, PAR is not routinely measured in most meteorological stations in the world. This is also the case in Singapore, where PAR is not measured in any of the 57 weather stations distributed across the city under the management of the national Meteorological Services Division. The worldwide network for measurement of PAR is apparently

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also limited to few locations (Frouin and Pinker 1995; Hu and Wang 2014), leading to the need to estimate PAR using various approaches. A widely used approach is to estimate PAR from global solar radiation (H, J m^{-2} time^{-1}) using the ratio of PAR to H (PAR/H), where PAR/H can be expressed in energy unit or in photon unit (μmol J^{-1}). A PAR/H of 0.5 in energy unit was suggested for practical purposes in the earlier studies of Monteith (1972), to be a reasonably conservative figure for both tropical and temperate regions. PAR/H has since then been shown to be geographically variable (Jacovides et al. 2007), is dependent on local atmospheric conditions, in particular cloud cover (Stigter and Musabilha 1982), sky conditions (Jacovides et al. 2004), aerosols (Jacovides et al. 1997) and varies diurnally and seasonally (Ge et al. 2011; Papaioannou et al. 1996). Where H is not available through direct measurements by pyranometers, it can be estimated from Angström-type equations using sunshine hours, which is widely captured in meteorological measurements and for which there are numerous variations in the formulae (Bakirci 2009). A second approach for estimation of PAR is through empirical relationships between PAR and other meteorological variables, such as the clearness index, k_t (ratio of global solar radiation, H to extraterrestrial solar radiation, H_o) (Cho et al. 2010; Hu and Wang 2014) and temperature and rainfall (Nöjd and Hari 2001). Increasingly, PAR has also been estimated using remote sensing data from satellites (Cai et al. 2014; Frouin and Pinker 1995), which has the advantage of wide spatial coverage but which correspondingly may not have adequate spatial resolution for micro-scale applications in urban regions. In addition, the artificial neural network method which is a widely accepted novel approach offering an alternative way to synthesise complex problems, can be also used for PAR radiant flux predictions (Jacovides et al. 2015; López et al. 2001). All the above four approaches point to the need for location-specific determination of PAR, albeit at an accuracy level that is appropriate for its application.

We describe in this paper the characteristics of PAR in Singapore and a comparison of methods for its estimation using a range of approaches. We believe this to be the first report on the assessment of PAR in Singapore. This is part of a larger study to understand the spatial and temporal characteristics of PAR in urban areas, how PAR is differentially affected by complexities of urban forms in a compact and high-rise city like Singapore, and how variations in PAR might in turn be correlated with the performance of urban green spaces (Tan and Ismail 2014; Tan and Ismail Under Review). In this study, our objectives were (1) to characterise the diurnal and seasonal variation in PAR and PAR/H in Singapore and (2) to compare methods for estimation of PAR under unshaded and shaded conditions in urban areas. Estimation of PAR under shaded conditions is necessary due to the ubiquity of shade in urban areas and the difficulty of deriving shaded PAR levels from unshaded levels because of spatial and temporal variations arising from the complexity of urban forms. We evaluated the efficacy of estimating PAR under shaded conditions using a commonly used variable in urban climatic studies, the sky view factor (SVF). For PAR estimation under unshaded conditions, we evaluated the use of empirically determined (1) PAR/H, (2) PAR/L (ratio of PAR to photometric radiation (L)) and (3) relationship between PAR, H and clearness index (k_t). Through these studies, we aim to develop a better understanding of PAR under the climatic conditions of Singapore and determine suitable methods for its estimation and application in vegetation-climate models and other studies in Singapore.

2 Methodology

2.1 Study sites and data utilised

For the assessment of unshaded solar radiation, a concrete roof (NUS) fully exposed to the sky in the National University of Singapore (1° 17.016′ N, 103° 46.003′ E; estimated 33 m above mean sea level) was used for measurement of H (J m^{-2} s^{-1}), PAR (μmol m^{-2} s^{-1}) and photometric radiation L in lux (lx). H was measured using a SPN1 Sunshine Pyranometer (Delta-T Devices, Burwell, Cambridge, UK); PAR was measured using a Photosynthetic Light (PAR) Smart Sensor S-LIA-M-003 (Onset, Bourne, Massachusetts, USA), and L was measured using a LI-200 Photometric Sensor (LICOR Inc., Lincoln, Nebraska, USA). SPN1 has a cosine correction error of ±2 % for solar radiation over solar zenith angle of 0° to 90° based on manufacturer's information. It also recorded diffuse radiation and sunshine hours based on World Meteorological Organisation's threshold of 120 W m^{-2} (WMO 2008). The sensors were factory calibrated prior to use. Table 1 shows the specifications of the sensors used. Data for the different sensors were continuously and

Table 1 Specifications of sensors used for studies based on manufacturer's information

	SPN1	PAR S-LIA-M003	LI-210
Spectral response	400–2700 nm	400–700 nm	400–700 nm
Sensitivity/resolution	0.6 W m^{-2}	2.5 μmol m^{-2} s^{-1}	30 μA 100 klux^{-1}
Relative error	±5 % for daily integral and ±8 % for hourly averages	±5 %	±5 %

simultaneously logged using GP1 data logger (Delta-T Devices, Burwell, Cambridge, UK) for SPN1, HOBO Micro Station Data Logger H21-002 (Onset, Bourne, Massachusetts, USA) for Smart Sensor S-LIA-M-003 and LI-1400 data logger (LICOR Inc., Lincoln, Nebraska, USA) logger for LI-200. For each sensor, data was sampled every minute and logged every 15 min between 1 November 2012 and 30 April 2014. Aggregated data was used to derive hourly, daily and monthly figures. Only data recorded between 0700 and 1900 hours was used as H and PAR values dropped to very low levels outside this time period. Data from 1 January 2013 to 31 December 2013 was used for development of models for estimation of PAR. The remaining data for 1 November 2012 to 31 December 2012 and 1 January 2014 to 30 April 2014 were pooled for verification of the models. Additional meteorological data from 1 January 2013 to 31 December 2013 was sourced from Changi Meteorological Station (1° 22.066′ N, 103° 58.936′ E) (http://app2.nea.gov.sg/weather-climate/climate-information/weather-statistics) for analysis of PAR data.

For the assessment of shaded PAR, a total of 15 urban sites were used, covering a range of urban forms in which shading of urban green spaces is experienced. These sites include at-grade community gardens, rooftop community gardens, landscaped sky terraces, landscaped areas under vehicular viaducts and flyovers and street canyon, using data collected in Tan and Ismail (Under Review). Additional data from an unpublished study on PAR under viaducts and flyovers was also incorporated for analysis. For each site, PAR was measured for a minimum of 7 days continuously at five to seven spots per study site with different PAR levels using the Smart Sensor S-LIA-M-003 sensors. SVF was measured at the same spots in which quantum sensors were installed. Defined as the fraction of the overlying hemisphere occupied by the sky (Oke 1981), SVF determines solar insolation in built surfaces within the urban fabric, and this is in turn determined by urban form such as building height, build-area coverage, building density and orientation (Elnahas 2003; Yuan and Chen 2011). SVF was determined using a classical method by taking skyward images and calculating the percentage of visible sky (Lin et al. 2012). The images were taken at a height of approximately at 1.5 m within a distance of 0.5 m from installed quantum sensors. Images were captured using a Nikon D80 Digital SLR (effective pixels, 10.2 million) with a Nikon 10.5 mm f/2.8 G ED fisheye lens and converted to black and white images with Adobe Photoshop CS6. SVF was then calculated in Rayman (version 1.2) using these images. A total of 95 sets of measurements were collected in the 15 sites, of which 50 were randomly selected for development of model between SVF and PAR and the remaining used to test the model.

2.2 Estimation of PAR

Unshaded PAR was estimated using several approaches. The first approach estimated PAR directly from H using PAR/H (mol MJ^{-1}). PAR/H was derived from hourly and daily H and simultaneously measured PAR using linear regression. The second approach used the empirical relationship between PAR and k_t of the form described in Aguiar et al. (2012), which parameterises PAR as a function of H and k_t in a multi-variable equation. We find this to be a useful empirical function given its simplicity, the ability to estimate PAR even when directly measured H is not available and that there are clear relationships between PAR and k_t (Aguiar et al. 2012; Hu and Wang 2014; Jacovides et al. 2007). The incorporation of k_t may therefore improve the accuracy of prediction of PAR from H. The equation used, as described in Aguiar et al. (2012), follows this form:

$$\mathrm{PAR} = a{\cdot}H{\cdot} + b{\cdot}k_t + c \tag{1}$$

where a, b and c are constants determined by non-linear regression curve fitting procedure in SPSS between measured PAR to measured H and calculated k_t. k_t was calculated using daily H measured at NUS, whereas daily H_o was calculated following Almorox and Hontoria (2004) with Eq. (2) at latitude ϕ for NUS:

$$H_o = (1/\pi){\cdot}G_{sc}{\cdot}E_o{\cdot}(\cos\phi{\cdot}\cos\delta{\cdot}\sin w_s + (\pi/180){\cdot}\sin\phi{\cdot}\sin\delta{\cdot}w_s) \tag{2}$$

where, G_{sc} is the solar constant with a generally accepted value of 1367 W m^{-2} (converted to 118.108 MJ m^{-2} day^{-1}), E_o is the eccentricity correction factor calculated from:

$$E_0 = 1.00011 + 0.034221{\cdot}\cos\tau + 0.00128{\cdot}\sin\tau + 0.000719{\cdot}\cos 2\tau + 0.000077{\cdot}\sin 2\tau \tag{3}$$

δ is the solar declination computed in degrees from:

$$\delta = (180/\pi){\cdot}(0.006918 - 0.399912{\cdot}\cos\tau + 0.070257{\cdot}\sin\tau - 0.006758{\cdot}\cos 2\tau +) \quad 0.000907{\cdot}\sin 2\tau - 0.002697{\cdot}\cos 3\tau + 0.00148{\cdot}3\tau) \tag{4}$$

where $\tau = 2\pi{\cdot}(n-1)/365$ (radians), n is the number of day of the year from first of January and w_s, the mean sunrise hour angle for the month, is calculated in degrees from:

$$w_s = \cos^{-1}(-\tan\phi{\cdot}\tan\delta) \tag{5}$$

The third approach for estimating PAR in unshaded conditions was developed from deriving the ratio, PAR/L (mol

Mlx^{-1} m^{-2}) from direct measurements to estimate PAR from photometric measurements. The fourth approach for estimating PAR in shaded areas used a linear regression model derived from measured daily PAR and SVF data. All statistical analyses were carried out using IBM SPSS Statistics 22 (IBM Corporation, Somers, New York, USA). Tests of statistical significance and correlations were done at 95 % confidence interval.

3 Results and discussion

3.1 Diurnal and seasonal variation of PAR and PAR/*H*

Given Singapore's equatorial position, *H* and PAR are not expected to show significant seasonal variations, as shown by our results (Fig. 1a). The month to month standard deviation in *H* was 1.76 MJ m^{-2} day^{-1}, which was about 11 % of the

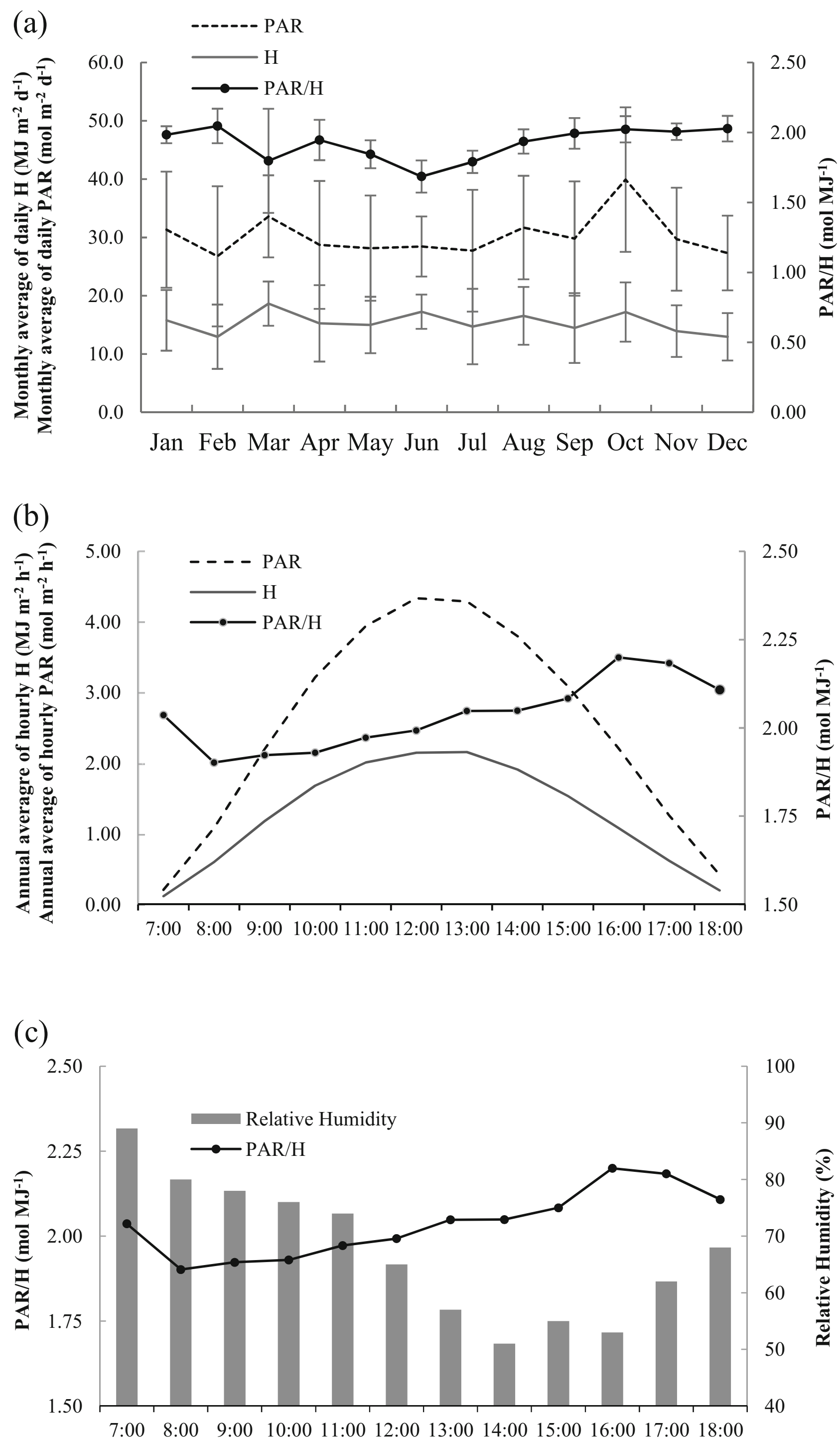

Fig. 1 Variation of *H*, PAR and *PAR/H* **a** annually, **b** diurnally and **c** with relative humidity. Relative humidity data was extracted from Wong et al. (2003)

annual mean of daily H (15.4 MJ m^{-2} day^{-1}). For PAR, this was 3.64 mol m^{-2} day^{-1}, about 12 % of the annual mean of daily PAR (30.7 mol m^{-2} day^{-1}). These low monthly variations are consistent with other solar radiation data reported for Singapore (Tan and Goh 1977; Wittkopf et al. 2004). There were however, noticeably lower values of H and PAR in November and December, which are the typical monsoonal months with higher than average rainfall. In 2013, H and PAR were also lower in February, which can be attributed to the atypically high monthly rainfall that was 150 % higher than the 143-year mean (NEA 2014).

While solar radiation is relatively uniform seasonally, daily variation is expected to be variable because of Singapore's equatorial conditions (Wittkopf and Soon 2007). Daily values of H and PAR showed fairly large variations within a month, as shown in the relatively large standard deviations that were as high as 43 and 41 % of the monthly means of the daily H and PAR, respectively (Fig. 1a). Such a day-to-day variation is also apparent in the 14-year data of global solar radiation in Tan and Goh (1977), and reflects the high variability of weather systems in the equatorial region, confounded by Singapore as an island with a small land mass. Diurnal pattern of H and PAR (Fig. 1b) showed a general symmetry around midday, where H peaked at 1300 hours whereas PAR peaked at 1200 hours.

PAR/*H* was determined by linear regression between PAR and H using two sets of aggregated data: daily averages (Fig. 2a) and hourly averages (Fig. 2b). While both sets of data showed strong linear and significant relationships ($P<0.001$), it was clear that hourly data was more variable than daily data around the mean. This was reflected in the lower coefficient of determination for hourly ($R^2=0.971$) compared with daily data ($R^2=0.991$). Similarly for photometric data, hourly data showed larger variation around the mean (Fig. 2d) compared with daily data (Fig. 2c). Hence, only daily data was used in subsequent analysis. *PAR*/*H* value of 1.867 mol^{-1} MJ was obtained from the linear regression of daily values. We compared this value with other studies conducted in the tropics (within latitudes 23.5° N and 23.5° N) (Table 2). Our study site is the closest to the equator and has the lowest *PAR*/*H* reported among these studies, although it is not the lowest reported worldwide. For instance, *PAR*/*H* of 1.87 mol MJ^{-1} was reported in Hu and Wang (2014) and Jacovides et al. (2004), albeit under different climatic and sky conditions. Several possible reasons could explain the differences in *PAR*/*H* between studies. Firstly, there might be methodological differences in the derivation of *PAR*/*H* highlighted by Udo and Aro (1999). While we used linear regression through the origin to derive *PAR*/*H*, the three other studies used averages of *PAR*/*H* values over hourly, daily or

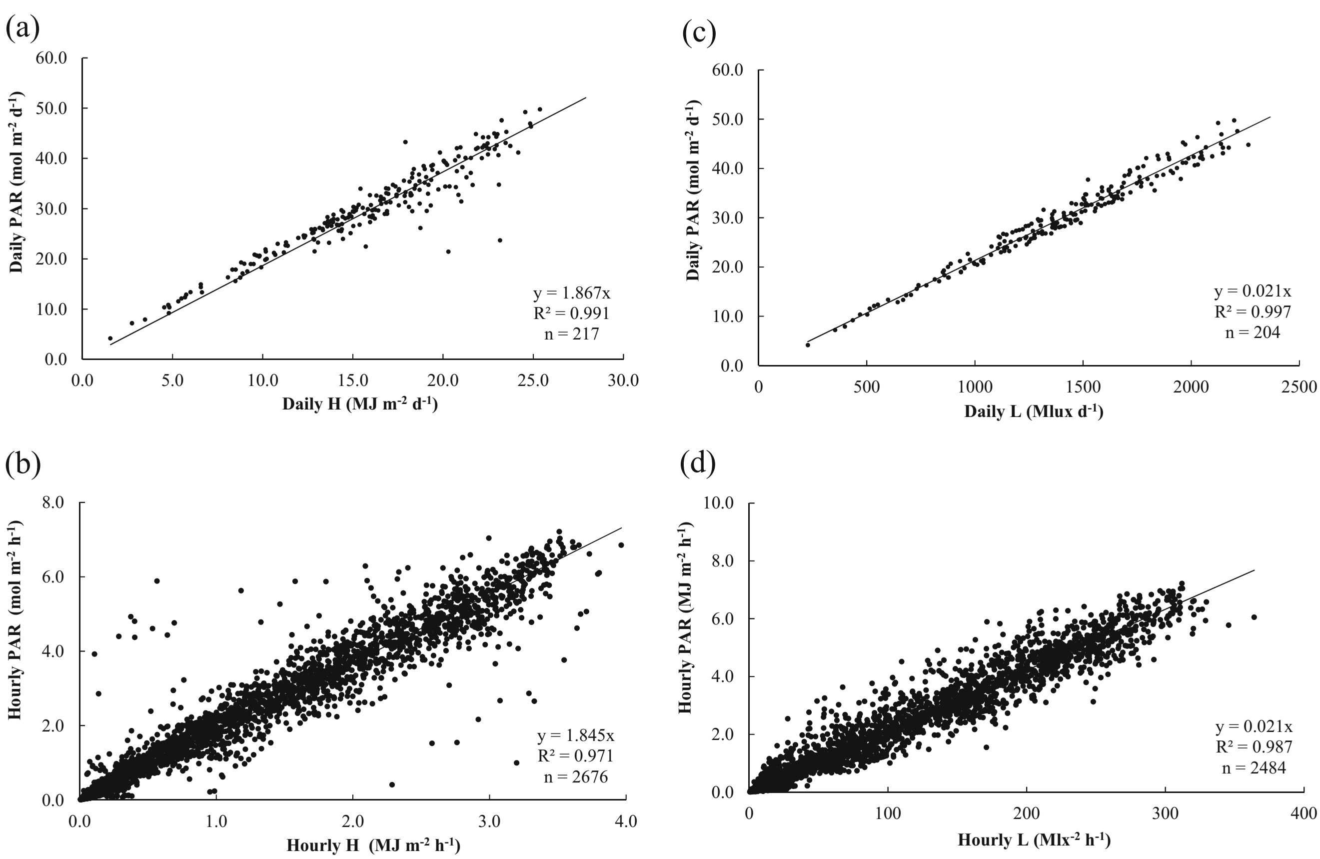

Fig. 2 Scatter plot of **a** daily PAR with daily H, **b** hourly PAR with hourly H, **c** daily PAR with daily L and **d** hourly PAR and hourly L

Table 2 Comparison of *PAR*/*H* between studies conducted in the tropical region (between 23.5° N and 23.5° S). Where studies expressed *PAR*/*H* in energy units, these were converted to *PAR*/H in mol MJ^{-1} using conversion factor of 0.2195 (MJ mol^{-1}) (Ross and Sulev 2000)

PAR/*H* (mol^{-1} MJ)	Method of derivation	Sky conditions/ period of aggregation	Location	Source
1.867	Linear regression	All/daily values	Singapore—1° 17.016′ N, 103° 46.003′ E	This study
1.923	Average of *PAR*/*H*	All/daily values	Singapore—1° 17.016′ N, 103° 46.003′ E	This study
2.08	Average of *PAR*/*H*	All sky/daily values	Nigeria—8° 32′ N, 4° 34′ E	Udo and Aro (1999)
2.10	Average of *PAR*/*H*	Clear/hourly values	Nigeria—8° 32′ N, 4° 34′ E	Udo and Aro (1999)
2.17	Average of *PAR*/*H*	Cloudy/hourly values	Nigeria—8° 32′ N, 4° 34′ E	Udo and Aro (1999)
2.32 (converted from energy ratio)	Average of *PAR*/*H*	Clear/hourly values	Tanzania 6° 49′ S, 39° 16′ E	Stigter and Musabilha (1982)
2.87 (converted from energy ratio)	Average of *PAR*/*H*	Cloudy/hourly values	Tanzania—6° 49′ S, 39° 16′ E	Stigter and Musabilha (1982)
2.17–2.29 (extracted data converted from energy ratio)	Average of *PAR*/*H*	All sky during wet season/hourly values	Brazilian Amazon pasture site—10° 45′ S, 62° 21′ W	Aguiar et al. (2012)
1.83–2.06 (extracted data converted from energy ratio	Average of *PAR*/*H*	All sky during dry season/hourly values	Brazilian Amazon pasture site—10° 45′ S, 62° 21′ W	Aguiar et al. (2012)

monthly periods. Our own results point to differences in *PAR*/*H* depending on calculation methods, as the monthly average of daily *PAR*/*H* ratios led to a higher *PAR*/*H* of 1.923 (Table 2). In addition, there were also differences in *PAR*/*H* derived from daily or hourly values even from the same data set, highlighting an important point that comparison of *PAR*/*H* between studies need to recognise differences in calculation methods (Udo and Aro 1999). Secondly, given that PAR is influenced by sky conditions, aerosols and altitudinal differences, localised differences between study sites may also contribute to the observed differences. However, the role of these factors cannot be easily delineated until much larger global datasets are available for meta-analysis. Thirdly, differences in quantum sensors may also contribute to differences in *PAR*/*H* (Ross and Sulev 2000). To date, there is no universal standard for ideal quantum sensors. *PAR*/*H* in our study is comparatively low despite a high diffuse component of solar radiation that is present in Singapore. As an island, the presence of surrounding water bodies leads to high evaporation, cloud formation and high humidity (Wittkopf and Soon 2007), factors that tend to increase *PAR*/*H* values compared with clear sky (Alados et al. 1996). Our data for 2013 showed that the annual average daily percentage of diffuse to global solar radiation is 61 % (data not shown), which agrees well with 63 % reported by Wittkopf et al. (2004), in contrast to 38 to 43 % for Osaka, Munich, Darwin and London. Despite the high diffuse radiation component of Singapore, *PAR*/*H* was still lower than PAR under clear-sky conditions reported in Stigter and Musabilha (1982) and Udo and Aro (1999). It should be noted too that a high diffuse radiation component arising from aerosols can also have the effect of reducing *PAR*/*H,* as scattering by aerosols affect the PAR spectrum more than longer wavelengths (Alados et al. 1996). The differential effects of clouds and aerosols on diffuse radiation have been reported (Min 2005) and their relative roles in influencing *PAR*/*H* in Singapore will need to be further studied.

The monthly average of daily *PAR*/*H* varied during the year between 1.686±0.021 and 2.046±0.047 mol MJ^{-1} (mean± standard error) (Fig. 1a). Overall, we expect the experimental error to be ±5 % based on the declared relative error of SPN1 and S-LIA-M-00 (Table 1). *PAR*/*H* was slightly higher in the wetter months of February, October, November and December than typical drier months of June and July (NEA 2014). In fact, when we compared monthly average of *PAR*/*H* with monthly average of daily rainfall from Changi Meteorological Station, the month-to-month variations between *PAR*/*H* and rainfall level were quite well-aligned, with both showing a clear depression from May to August and a rise from October to December and in February (Fig. 3). That *PAR*/*H* is higher in wetter months than drier months is well documented in different geographical locations (Aguiar et al. 2012; Jacovides et al. 2007; Udo and Aro 1999). This is explained by the preferential absorption of longer wavelengths by water vapor, which reduces *H* more than PAR (Alados et al. 1996, 2000).

In our data, the maximum deviation of daily *PAR*/*H* from the annual mean was about 12 % in June, which is much lower

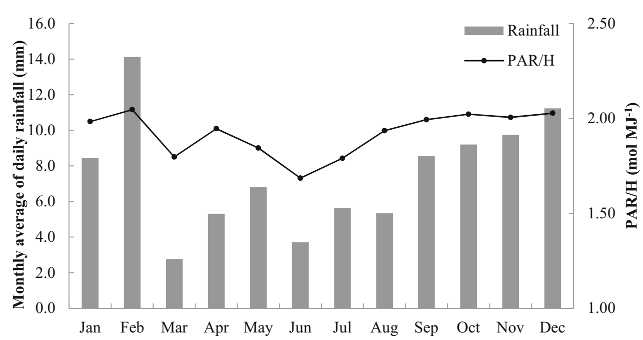

Fig. 3 Seasonal variation of daily PAR/*H* with daily rainfall

than seasonal variations of *PAR*/*H* reported in higher latitudes, for instance in Hu and Wang (2014), but closer to the month-to-month variations in the tropics, for instance in Aguiar et al. (2012) and Udo and Aro (1999). Our data also showed clear relationships between PAR and *H* with the proportion of diffuse radiation (H_d) to *H* (K_d). As *H* decreases proportionately more than PAR with increasing K_d (Fig. 4a), *PAR*/*H* consequently increases slightly with increasing K_d ($P<0.001$) (Fig. 4b). K_d also expectedly showed a strong negative linear relationship with clearness index k_t (Fig. 4c), since k_t aggregates the meteorological effects of aerosols, water vapour and clouds in the attenuation of solar radiation by the atmosphere (Liu and Jordan 1960), factors that also contribute to scattering of solar radiation.

Diurnally, *PAR*/*H* showed a slight increasing trend over the day (Fig. 1b), with a maximum variation of 7 % between the daily mean and hourly mean. This indicates that as the day progresses, atmospheric conditions tend to reduce *H* more

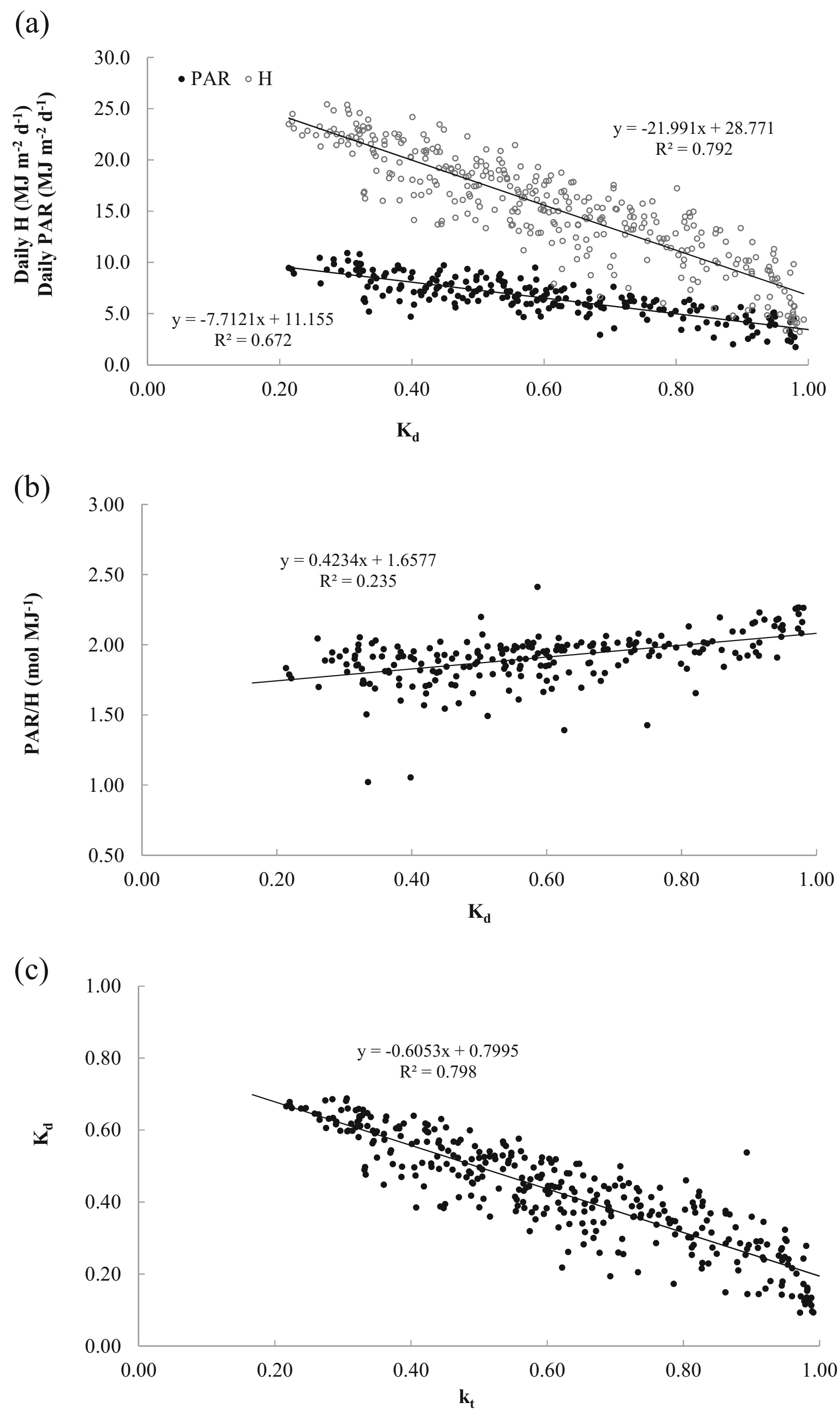

Fig. 4 **a** Relationship between PAR and *H* with percentage of diffuse to global solar radiation (K_d). Note that PAR is expressed in energy units using conversion factor of 0.2195 MJ mol^{-1} (Ross and Sulev 2000) for ease of comparison with *H*. **b** Relationship between *PAR*/*H* with percentage of diffuse to global solar radiation (K_d). **c** Relationship between percentage of diffuse to global solar radiation (K_d) to clearness index (k_t)

than PAR, leading to an increase in *PAR*/*H* that has been observed. The diurnal variation in *PAR*/*H* is variable between sites, e.g. with different degrees of midday depression (Alados et al. 1996; Jacovides et al. 2004; Udo and Aro 1999), midday increase (Ge et al. 2011), slight increasing trend throughout the day (Aguiar et al. 2012), as well as inconsistent diurnal changes from month to month (Bat-oyun et al. 2012). The most commonly cited factor that explains the diurnal variation is water vapour. This however, did not seem to fully explain the changes in diurnal changes in *PAR*/*H* in this study. We compared *PAR*/*H* to relative humidity (RH) data which was recorded on an exposed roof in the western region of Singapore about 4 km from NUS (Wong et al. 2003). RH dropped steadily till about 1400 hours, following which it increased gradually (Fig. 1c) to repeat the diurnal cycle. A similar diurnal pattern in RH is also observed in Hawlader et al. (1990). The increase in RH from 1400 hours onwards correlated with increasing *PAR*/*H*, but RH changes do not correlate with expected changes in *PAR*/*H* in the earlier part of the day. Further studies with simultaneous and co-located measurements will be needed to verify this observation, as well as to identify other possible factors, such as haze, that might affect the atmospheric conditions and fluctuations in hourly *PAR*/*H*.

Our study also derived an empirical value for *PAR*/*L* of 0.021 mol Mlx^{-1} m^{-2} under Singapore's sky conditions. Conversion of PAR from photometric measurements are often needed to interpret earlier reports using photometric and other radiometric measurements (Thimijan and Heins 1983) and in the field of urban design where photometric measurements are commonly used for daylighting studies. A locally derived *PAR*/*L* is thus useful for such applications. *PAR*/*L* values derived in this study were the same from both hourly and daily measurements, with high coefficient of determination (Fig. 2c, d). As few reports of *PAR*/*L* have been published, comparison of our results across geographical regions is limited. A comparison with reports of Thimijan and Heins (1983) and Biggs (1986), with *PAR*/*L* of 0.019 mol Mlx^{-1} m^{-2} and 0.018 mol Mlx^{-1} m^{-2}, respectively, indicates that *PAR*/*L* is higher under Singapore's sky conditions.

3.2 Estimation of PAR

PAR was estimated using four approaches and compared with measured PAR using several statistical measures: coefficient of determination (R^2), root mean square error (RMSE), mean bias error (MBE) and mean percentage error (MPE). All input variables used daily values. The first approach used the equation:

$$\mathrm{PAR} = 1.867 \cdot H \tag{6}$$

The second approach used the equation:

$$\mathrm{PAR} = 3.281 \cdot H - 57.711 \cdot k_t + 3.389 \tag{7}$$

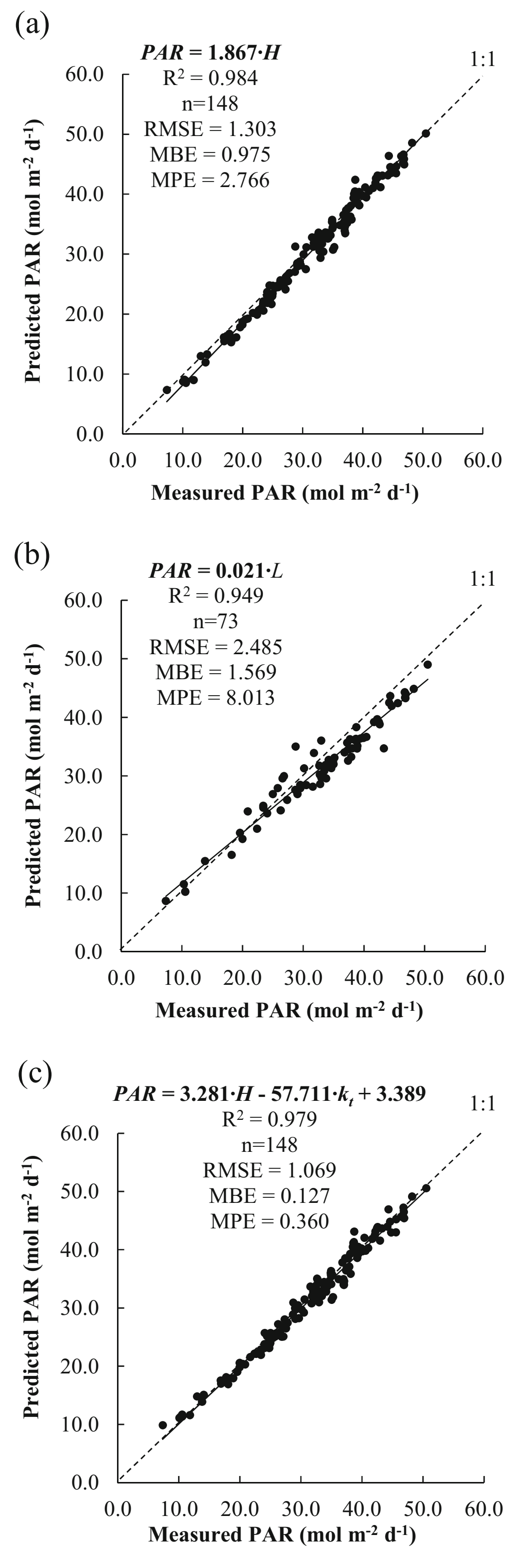

Fig. 5 Comparison of predicted daily PAR with measured daily PAR for three models: **a** using *PAR*/*H*, **b** using *PAR*/*L*, and **c** using *H* and k_t

Table 3 Statistical measures for comparison of goodness of fit and accuracy of models for estimation of PAR

	R^2	RMSE[a] (mol m^{-2} day^{-1})	MBE[b] (mol m^{-2} day^{-1})	MPE[c] (%)	Number
PAR=1.867H	0.984	1.303	0.975	2.766	148
PAR=3.281 H−57.711 k_t+3.389	0.979	1.069	0.127	0.360	148
PAR=0.021 L	0.949	2.485	1.569	8.013	73

[a] $\mathrm{RMSE} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(measured_i - predicted_i)}\ ^2$

[b] $\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}(measured_i - predicted_i)$

[c] $\mathrm{MPE} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{measured_i - predicted_i}{predicted_i}\right)\cdot 100$

The third approach used the equation:

$$\mathrm{PAR} = 0.021 \cdot L \tag{8}$$

All three models produced good and statistically significant (P<0.001) fit between measured and predicted PAR (Fig. 5), with R^2 higher than 0.94, and high accuracy of estimation (with MPE of 0.36–8.013 %) (Table 3). However, as shown by positive MBE and MPE, all models tend to underestimate PAR slightly. Across the full range of statistical measures, estimation with photometric radiation produced the lowest level of fit and highest amount of error or bias. Estimation with derived PAR/H ratio performed well, and the inclusion of k_t achieved the best fit and lowest amount of bias. This is not surprising as from Fig. 4, PAR/H is expected to also have an inverse relationship with k_t, i.e. k_t explains part of the variations in H. This has been shown in several studies as a logarithmic relationship (Alados et al. 1996; Jacovides et al. 2007) or inverse linear relationship within certain range of k_t (Li et al. 2010). The improvement in the accuracy of estimation of PAR with k_t is also in alignment with the study by Hu and Wang (2014).

For the estimation of PAR in shaded urban areas, the use of SVF was shown in a preliminary study to have a good

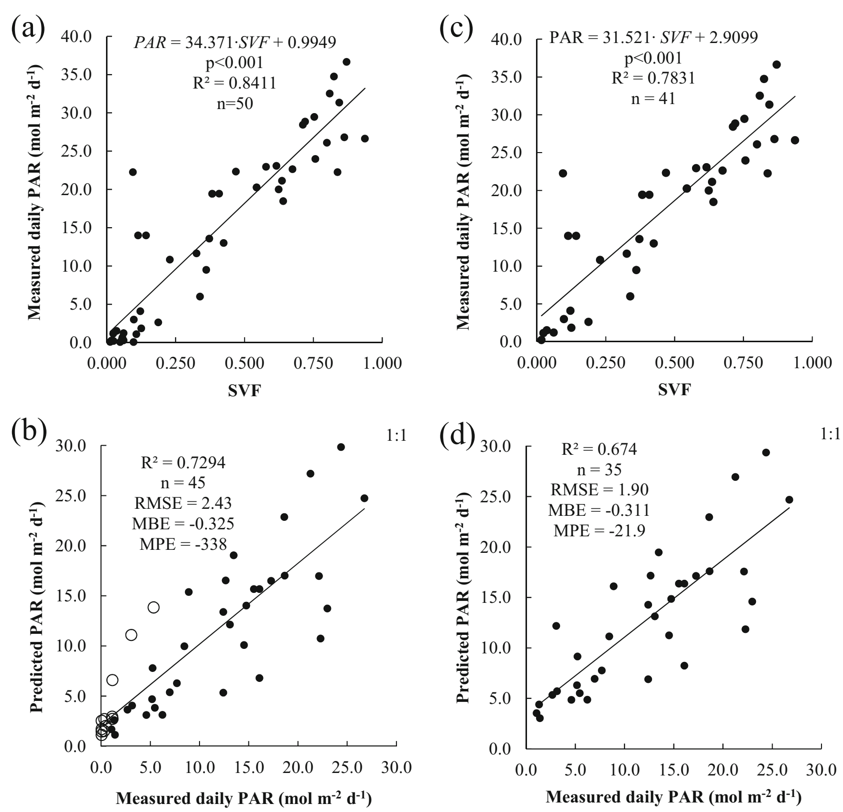

Fig. 6 **a** Relationship between daily PAR under shaded conditions and SVF; **b** comparison of predicted versus measured daily PAR developed using model in (**a**). *Enlarged open circles* are points with MPE >100 %; **c** relationship between daily PAR and SVF with data points removed for PAR <1.2 mol m^{-2} d^{-1}; **d** comparison of predicted versus measured daily PAR using model in (**c**). Units for RMSE and MBE are mol m^{-2} d^{-1} and percentage for MPE

correlation with daily PAR (Tan and Ismail Under Review). We expanded our measurements to cover a total of 95 distinct measurement points across a range of shaded urban conditions in this study. Our results verified the strong linear relationship between SVF and daily PAR (Fig. 6a), producing a linear equation shown in the figure. When this equation was used for estimation of daily PAR from SVF, there was also a significant linear relationship between measured and predicted but with clear scatter of points around the 1:1 line (Fig. 6b). Other statistical measures: RMSE of 2.43 mol m^{-2} d^{-1}, MBE of −0.325 mol m^{-2} d^{-1} and MPE of −338 % showed that PAR tends to be overestimated. The very large MPE suggests that the model is prone to marked differences between individual pairs measured and predicted PAR at low levels of PAR less than 1.2 mol m^{-2} d^{-1} (cluster of points shown in open circles in Fig. 6b) and cannot be used for adequately precise estimation of shaded PAR at these levels. This could be due to a relatively short measurement period of around 7 days for the measurement of daily PAR, which was inadequate to capture the typical average daily PAR level due to low PAR levels during the periods of measurements. More studies with longer period of measurements are suggested to improve the estimation model. When data points with PAR higher than 1.2 mol m^{-2} d^{-1} were excluded and the new linear equation used for estimation of PAR (Fig. 6c), all statistical measures with the exception of R^2 improved, particularly MPE which was reduced significantly (Fig. 6d).

4 Conclusions

We reported in this study, the first published assessment of PAR and *PAR*/*H* in Singapore. PAR measured over a 1-year period in Singapore showed good correlation with global solar radiation, an observation also reported in different geographical regions. There was a higher correlation with between H and daily PAR than with hourly PAR, which likely reflects the high level of fluctuation in atmospheric conditions at the hourly level due to Singapore's small land mass as an island and its equatorial conditions. Fluctuations in seasonal daily PAR of 12 % around the annual daily mean is comparatively lower than levels reported in other studies at higher latitudes. Daily *PAR*/*H* also showed seasonal fluctuations which correlated well with monthly rainfall levels, suggesting a strong role in rainfall in influencing the sky conditions of Singapore. Diurnal *PAR*/*H* increased throughout the day, which seemed to be only partially related to RH, although this requires further studies using simultaneous measurements for verification. *PAR*/*H* of 1.867 mol MJ^{-1} derived from linear regression is low compared with results from other tropical regions. Several reasons were offered for this observation.

The models developed in this study were able to predict unshaded PAR satisfactorily using a range of input variables: daily H, daily L and daily k_t, with the models achieving low RMSE error of 1.069–2.495 mol m^{-2} day^{-1} and MPE of 0.360–8.013 %. The model which combined H and k_t as input variables achieved the lowest RMSE, MPE and MBE, and the highest R^2, indicating that in addition to the well-accepted variation of PAR with H, the inclusion of k_t as a measure of the sky conditions was able to explain a higher level of variations in PAR and reduced the bias in model. As k_t can be calculated for any location with known latitude without additional meteorological data, Eq. (7) can be applied readily in Singapore. For shaded PAR, while the linear regression model between daily PAR and SVF achieved satisfactory R^2, RMSE and MBE. MPE as a measure of the average percentage of error in the prediction was very large, which was mainly due to large differences between predicted and measured PAR values at low levels of PAR for a number of pairs of measurements. For PAR levels higher than 1.2 mol m^{-2} day^{-1}, SVF is a satisfactory predictor of daily PAR. Further studies that can establish a more accurate model, e.g. through longer periods of PAR measurements to reduce the effect of short, temporal variations in sky conditions are needed.

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