Environmental dependence and seasonal variation of diffuse solar radiation in tropical peatland

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Abstract

Changes in cloud cover and atmospheric aerosol loading strongly affect the diffuse proportion of solar radiation (R_d/R_g). It has been reported that plant photosynthesis is more efficient under diffuse light conditions, but diffuse radiation (R_d) regimes in tropical peatland frequently subjected to large-scale fires are poorly described, and there are few or no site-based datasets to date. Therefore, we continuously measured R_d for more than three years at a burnt ex-forest on tropical peatland in Central Kalimantan, Indonesia. Daily R_d/R_g was significantly related to the clearness index (R_g/R_o) with a linear threshold model. The model parameters showed that R_d/R_g under a clear sky is larger in tropical peatland with a humid climate than in Australia. Using the model, long-term variation in R_d/R_g for more than 12 years was estimated from R_g measured above a nearby forest. As a result, R_d/R_g showed a seasonal variation with its minimum of 0.51 in June (the transition between the wet and dry seasons) and its maximum of 0.68 in October (the late dry season) on a monthly basis. The decreasing pattern from the late wet season to the early dry season corresponded to decreasing precipitation due to fewer clouds. In contrast, the increasing pattern through the latter half of the dry season was due to shading by smoke emitted through burning biomass and peat fires. In particular, during the El Niño droughts in 2002, 2006 and 2009, the monthly mean R_d/R_g rose above 0.72, because the ground was densely covered with smoke from large-scale fires.

Key words: Aerosol, Clearness index, El Niño drought, Peat fire, Smoke.

1. Introduction

Peatlands are carbon-dense ecosystems that are vulnerable to disturbances through human activities and climate change. In the tropics, peatlands are widely distributed over 4.41×10^5 km² (about 11% of global peatland area) and store soil carbon up to 88.6 Pg (15–19% of the global peat carbon pool) with 57.4 Pg of carbon stored in Indonesia (Page *et al.*, 2011). However, poor land management practices, such as logging, drainage and fires have disturbed tropical peatlands in Southeast Asia. In Indonesia, peat swamp forests of 2.76×10^4 km² were deforested and drained

for the last decade (Miettinen *et al.*, 2011). As a result, a large amount of CO₂ has been steadily emitted through less photosynthesis and more oxidative peat decomposition (Couwenberg *et al.*, 2009; Hooijer *et al.*, 2010; Hirano *et al.*, 2014). The fires are often triggered by lower groundwater levels (Putra *et al.*, 2008; Putra and Hayasaka, 2011) and land clearing (Murdiyarso and Adiningsih, 2007) in the late dry season, especially during El Niño droughts. Large-scale peat fires occurred in Sumatra and Central Kalimantan, Indonesia, in the El Niño years of 1997, 2002, 2006, and 2009 (Page *et al.*, 2002; van der Werf *et al.*, 2008; Ballhorn *et al.*, 2009; Langner *et al.*, 2009; Tosca *et al.*, 2011). Smoke and aerosol released to the atmosphere during peat fires attenuate global solar radiation (R_g) and increase fraction of diffuse solar radiation (R_d/R_g) on the ground. Increased diffuse radiation produces more uniform irradiance with smaller fractions of light-saturated leaves and penetrates deeper into the

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light-limited lower canopy, which results in an increase in the light-use efficiency of gross primary production (GPP) (Gu *et al.*, 2002; Knohl and Baldocchi, 2008; Oliphant *et al.*, 2011).

Some studies examined the effects of aerosol and clouds on radiation and their impacts on canopy gas exchange processes in temperate forests (Suzaki *et al.*, 2003; Knohl and Baldocchi, 2008; Matsui *et al.*, 2008; Still *et al.*, 2009) and tropical forests (Oliveira, *et al.*, 2007). For tropical peat swamp forest, Hirano *et al.* (2012) examined the effect of smoke from peat fires in 2006 on GPP using the light curve of GPP and the clearness index (R_g/R_o): the ratio of R_g and extra-terrestrial solar radiation (R_o), as an index of the fraction of the diffuse radiation (R_d) (Spitters *et al.*, 1986; Roderick, 1999). However, field information on R_d in tropical peatland, which are periodically covered by dense smoke through peat fires in response to El Niño drought, is quite limited.

Therefore, we continuously measured R_d along with other environmental elements in tropical peatland in Central Kalimantan, Indonesia for more than three years. Using the field data, we analyzed the relationships between R_d/R_g and environmental factors, and parameterized a linear threshold model (Roderick, 1999) to estimate R_d/R_g from R_g/R_o . Moreover, we examined seasonal variation in the radiation environment of tropical peatlands and the effect of smoke due to biomass burning and peat fires on R_d/R_g using long-term data of R_g from 2001 to 2013.

2. Materials and Methods

2.1 Site Description

The study was carried out at two sites (DF and DB) on tropical peatland in Central Kalimantan province, Indonesia. The sites were about 15 km apart from Palangkaraya, the capital of the province (Hirano *et al.*, 2012). The DF site (2°20'45.9"S, 114°2'11.1"E) with a 50 m high tower was located in a secondary forest remaining in Block C of the Mega Rice Project (MRP): a national project of peatland conversion into rice fields during the late 1990s. The DB site (2°20'26.9"S, 114°2'16.4"E) with a 4 m high tower was located in an ex-forest, which was burnt three times during El Niño droughts in 1997, 2002 and 2009. The two sites, described in detail by Hirano *et al.* (2012), were about 600 m away from each other. A large canal (25 m wide, 3.5–4.5 m deep), which was

excavated in 1996 and 1997, runs between the two sites and has functioned effectively to facilitate drainage.

Annual precipitation and annual mean air temperature from 2002 to 2009 were 2452 mm yr⁻¹ and 26.1°C, respectively (Hirano *et al.*, 2012). Although air temperature is mostly constant throughout the year, precipitation shows clear seasonality. According to a precipitation threshold of 100 mm month⁻¹ (e.g. Oldeman *et al.*, 1980), the dry season occurs, on average, for three to five months from June to October (Hirano *et al.*, 2007; Putra and Hayasaka, 2011), owing to the strong influence of the dry southeast monsoon (Aldrian and Sutanto, 2003). An El Niño event prolongs the dry season and raises the risk of large-scale peat fires by lowering groundwater levels (GWL). El Niño droughts occurred in 2002, 2006 and 2009 (Putra and Hayasaka, 2011; Hirano *et al.*, 2012).

2.2 Field data

Meteorology and GWL have been measured since July 2001 and April 2004, respectively, at DF and DB. At both sites, global solar radiation (R_g) and atmospheric radiation, or downward long-wave radiation, (R_a) were measured above the canopy with a radiometer (CNR-1; Kipp & Zonen, The Netherlands). On the other hand, R_g and diffuse radiation (R_d) have been measured with a sunshine sensor (BF3; Delta-T devices, UK) only at DB since March 2010; the data have some gaps due to sensor malfunction. In addition, air temperature, relative humidity, and precipitation were measured at heights of 41.7m and 1.5m, respectively, at DF and DB (Hirano *et al.*, 2007; Hirano *et al.*, 2012). Half-hourly means of meteorology and GWL, which were measured at intervals of 10 or 30 sec, were recorded with a data logger (CR10X; Campbell Scientific Inc., USA).

2.3 Data Analysis

Diffuse fraction (R_d/R_g) was calculated using outputs from BF3, whereas atmospheric transmission/clearness index (R_g/R_o) was determined from measured R_g with CNR1 and extra-terrestrial solar radiation (R_o) calculated according to Spitters *et al.* (1986), Roderick (1999), and Khan (2009), because a thermopile sensor (CNR1) is generally more reliable than a photodiode sensor (BF3) for R_g measurement.

The R_o (W m⁻²) was calculated using the following equations.

$$R_o = S_{sc}[1 + 0.033 \cos(360t_d/365)] \sin \beta, \quad (1)$$

$$\sin\beta = \sin\lambda \sin\delta + \cos\lambda \cos\delta \cos[15(t_h - 12)], \quad (2)$$

$$\sin\delta = -\sin(23.45^\circ) \cos[360(t_d + 10)/365], \quad (3)$$

$$t_h = LT + \frac{\omega}{60}, \quad (4)$$

$$\omega = 4(Long - LSTM) + \theta, \quad (5)$$

$$\theta = 9.87 \sin(2\varphi) - 7.53 \cos(\varphi) - 1.5 \sin(\varphi), \quad (6)$$

$$\varphi = \frac{360}{365}(t_d - 81), \quad (7)$$

where S_{sc} is solar constant (1370 W m^{-2}), β is solar altitude (deg.), t_d is Day of Year (DOY), λ is latitude (deg.), δ is solar declination (deg.), t_h is solar time (h), LT is local time (h), ω is a time correction factor (min), θ is the equation of time (min), $Long$ is longitude (deg.), $LSTM$ is the local standard time meridian (deg.) and φ is day angle (deg.).

The R_d/R_g depends on solar altitude and tends to increase as solar altitude declines because of an increase in optical path length. Thus, in half-hourly analysis, data around midday from 1000 to 1400 hours were only used to eliminate the effect of solar altitude. In addition, data during rain and within an hour after a rain event were excluded to minimize the interference from raindrops on the dome of radiometers. In daily and monthly analyses, R_d/R_g was calculated from the sums of all half-hourly data of R_d and R_g in the daytime.

To estimate R_d/R_g for a long period from R_g/R_o , we applied a simple linear threshold model (Roderick, 1999), described as:

$$\frac{R_d}{R_g} = Y_0 \text{ for } \frac{R_g}{R_o} \leq X_0, \quad (8a)$$

$$\frac{R_d}{R_g} = A_0 + A_1 \frac{R_g}{R_o} \text{ for } X_0 < \frac{R_g}{R_o} \leq X_1, \quad (8b)$$

$$\frac{R_d}{R_g} = Y_1 \text{ for } \frac{R_g}{R_o} \geq X_1, \quad (8c)$$

$$A_0 = Y_1 - A_1 X_1, \quad (8d)$$

$$A_1 = \frac{Y_1 - Y_0}{X_1 - X_0}, \quad (8e)$$

where R_d , R_g , and R_o are respective daily totals. The

parameters (X_0 , X_1 , Y_0 , Y_1 , A_0 , and A_1) were determined using the data measured at DB from March 2010 to December 2013. The Y_1 was set equal to the minimum value of R_d/R_g , which was 0.15. The Y_0 was determined by averaging R_d/R_g for days when R_g/R_o was less than 0.2. The A_0 and A_1 were determined by linear regression between R_d/R_g and R_g/R_o , when R_g/R_o was larger than 0.25. The X_1 and X_0 were subsequently derived from eqs. (8d) and (8e) (Roderick, 1999). Using the model, long-term R_d/R_g for more than 12 years were assessed from R_g measured at DF.

3. Results

3.1 Environmental dependence of diffuse fraction

Figure 1 shows the relationships of several radiation components with R_d/R_g around midday (1000–1400 h) in rainless conditions at DB. Direct radiation (R_b) was determined as a difference between R_g and R_d , which were measured with BF3. Under a constant value of R_o and R_a , R_g and the R_b decreased as R_d/R_g increased. The R_d continued to increase with R_d/R_g when the fraction was less than 0.8. In contrast, above the R_d/R_g value of 0.8, R_d decreased, whereas the decreasing rate was smaller than that in R_g . The decrease in R_d along with R_g indicates that R_d/R_g becomes saturated in overcast conditions.

To analyze the environmental dependence of R_d/R_g , it was plotted against R_g/R_o , vapor pressure deficit (VPD) at a height of 1.5m, R_a , groundwater level (GWL), and precipitation on half-hourly and daily bases (only a daily basis for precipitation) using DB data. Although no significant correlation was found with R_a , GWL and precipitation ($r^2 < 0.06$) (data not shown), R_d/R_g showed significant negative linearity ($p < 0.01$) with half-hourly R_g/R_o ($r^2 = 0.71$), daily R_g/R_o ($r^2 = 0.79$), half-hourly VPD ($r^2 = 0.34$), and daily VPD ($r^2 = 0.49$) (Fig. 2). The negative relationships indicate that R_d/R_g increases as aerosols and cloud particles increase, or the amount of water vapor increases through the enhancement of scattering. The r^2 values were higher on a daily basis for both R_g/R_o and VPD .

Fig. 1. Relationships between radiation components (R_o , R_g , R_b , R_a , and R_d) and the diffuse fraction (R_d/R_g) in rainless condition around midday (1000–1400 h) from March 2010 to December 2013 at DB site. R_o is extra-terrestrial solar radiation, R_g is global solar radiation, R_b is direct radiation, R_a is atmospheric radiation, and R_d is diffuse radiation.

3.2 Modeling of diffuse fraction

The linear threshold model described as Eq. (8) was parameterized on a daily basis and each parameter was determined to be $X_0 = 0.26$, $X_1 = 0.84$, $Y_0 = 0.96$, $Y_1 = 0.15$, $A_0 = 1.32$ and $A_1 = -1.39$ (Fig. 3). The r^2 value and root mean square error (RMSE) were 0.78 and 0.089, respectively. Simple linear correlation between R_d/R_g and R_g/R_o for all daily data showed r^2 of 0.77 ($p < 0.001$) and RMSE of 0.090, which means that the performance of the linear threshold model is slightly higher than the simple linear relationship. The linear correlation was also significant ($p < 0.001$) even using moving-average data for 5, 10, 15, and 30 days, whereas r^2 decreased from 0.72 to 0.69 as the number of days for averaging increased from 5 to 30 days. This significant linear relationship shows that R_g/R_o is an effective index for R_d/R_g , even on a monthly basis (Roderick, 1999).

3.3 Seasonal variation in diffuse fraction

The R_g measured with CNR1 was almost identical for DB and DF on a daily basis. Therefore, the linear threshold model parameterized using DB data is applicable to DF. The time sequence of monthly mean R_d/R_g , which were calculated based on daily data, is shown in Fig. 4 along with GWL and precipitation for more than 12 years. The R_d/R_g shows a relatively regular cycle

with an annual trough; monthly R_d/R_g becomes lower than its mean (0.62) in the early dry season. In addition, R_d/R_g shows sharp peaks above 0.72 in the El Niño years of 2002, 2006, and 2009. The peaks correspond to the large drops of GWL caused by El Niño droughts.

Monthly data at DF from 2001 to 2013 were ensemble-averaged to clarify seasonal variations (Fig. 5). A relatively large standard deviation of R_d/R_g for each month resulted from interannual variations in the seasonality of precipitation and the occurrence of peat fires, which were caused by El Niño and La Niña events. Monthly mean R_d/R_g began to decrease in April and reached its minimum of 0.51–0.52 in June and July, the transition between the wet and dry seasons. This decreasing pattern corresponded to decrease in precipitation and increase in VPD , which reflect decreasing amounts of cloud cover. During the dry season, monthly R_d/R_g gradually increased and reached its maximum of 0.68 in October, the transition between the dry and wet seasons. In October, GWL reached a negative peak of -0.91 m and daytime VPD (0900 to 1500 h) kept the largest level. The increase of R_d/R_g was due to smoke emitted through burning biomass and peat fires, especially during El Niño droughts, because precipitation remained low and daytime VPD remained high.

Fig. 2. Relationships between the diffuse fraction (R_d/R_g) and clearness index (R_g/R_o) or vapor pressure deficit (VPD) at DB on half-hourly (a and b) and daily (c and d) bases. For half-hourly relationships, data only in rainless condition around midday (1000 – 1400 h) are used.

Such a dry condition lowers GWL and raises the risk of peat fires (Putra and Hayasaka, 2011). Monthly mean R_d/R_g was lower than its annual mean of 0.62 for four consecutive months from May to August.

3.4 Effect of peat fires

Figure 6 shows seasonal variations in R_d/R_g , estimated from R_g/R_o , R_g , GWL , precipitation and daytime VPD at DB from July 1 (DOY182) to November 30 (DOY334) in 2009 (an El Niño year) and 2010 (a La Niña year). Sums of precipitation for the five months were 489 and 1633 mm, respectively, in 2009 and 2010, which caused a large interannual difference in daytime VPD; mean daytime VPDs were 19.4 and 12.6 hPa, respectively, in 2009 and 2010. In 2009, GWL remained below -0.25m throughout the five months. The GWL decreased continuously from July to early

October, with a negative peak of -1.15 m . In the dry condition, a series of peat fires occurred in August and grew up extensively in September and October (Yulianti *et al.*, 2012). Because dense smoke covered the ground, R_d/R_g continued to increase up to 0.8 between early August and mid-October regardless of fewer clouds, which was judged from a large number of rainless days. On the other hand, in 2010, GWL never lowered underground because of continual precipitation. As a result, no peat fires occurred in the five months, in which the dry season is usually included. Although R_d/R_g remained relatively high during the period because of more clouds in 2010, R_d/R_g in October and November was considerably higher in 2009 than in 2010. In addition, R_g in October and November was lower by 20% in 2009 because of smoke cover.

Fig. 3. Fitting of linear threshold model for the daily relationship between the diffuse fraction (R_d/R_g) and clearness index (R_g/R_o).

4. Discussion

The linear threshold model (Roderick, 1999) was parameterized for tropical peatland (2.3°S) in Indonesia (Fig. 3). The parameters of Y_0 (0.96) and X_0 (0.26), which stand for the saturated diffuse fraction (R_d/R_g) and the saturation point of clearness index (R_g/R_o), at which R_d/R_g becomes saturated, respectively, were the same as the means for 25 sites in Australia

and Antarctica (12.4°S–67.6°S) (Roderick, 1999). The Y_0 of 0.96 suggests that 4% of R_g reaches the ground as beam (R_b) even in overcast conditions. Our results of 0.15 and 0.84 for Y_1 and X_1 , respectively, were larger than the means for the 25 sites ($Y_1 = 0.05$ and $X_1 = 0.79$) (Roderick, 1999). The Y_1 and X_1 represent the minimum R_d/R_g and the upper limit of R_g/R_o for linearity with R_d/R_g , respectively. Roderick (1999) reported that X_1 depends on latitude in a quadratic

Fig. 4. Time sequences of monthly values of estimated diffuse fraction (R_d/R_g), precipitation, and groundwater level (GWL) at DF site from July 2001 to December 2013.

manner. According to his equation, X_1 can be calculated to be 0.80 for the latitude of 2.3°S , which is smaller than our result. Larger X_1 indicates larger R_d/R_g at a given R_g/R_o , if Y_1 is fixed. Also, larger Y_1 indicates larger R_d/R_g under a clear sky. The larger Y_1 and X_1 values for our site compared to those in Australia are chiefly attributable to the moist atmosphere with more water vapor in a tropical rainforest climate, defined as annual precipitation $> 1500 \text{ mm yr}^{-1}$ and dry season length $< \text{six months}$ (Lewis, 2006).

The R_d/R_g continued to decrease from the late wet season to the early dry season, and then increased during the latter half of the dry season (Fig. 5). The de-

creasing pattern was due to decreased cloud amount and higher VPD (Fig. 2). Such a seasonal variation in R_d/R_g in accordance with a precipitation pattern was also reported for Amazonian rainforests (Butt *et al.*, 2010). On the other hand, smoke shading due to the burning of biomass and peat also caused the increase in R_d/R_g . In this area of tropical peatland, most fires are human-caused and occur in the mid- to late dry seasons from August through October (Yulianti *et al.*, 2012). Thus, such human activities emit smoke and increases R_d/R_g even in the dry season with less precipitation. The fires often expand extensively during the prolonged dry season due to El Niño droughts, and conse-

Fig. 5. Mean seasonal variations in monthly values of the diffuse fraction (R_d/R_g) (a), global solar radiation (R_g) (b), precipitation (c), groundwater level (GWL) (d), daytime vapor pressure deficit (VPD) (0900–1500 h) (e) at DF site for 12 years from 2002 to 2013. Each vertical bar denotes one standard deviation.

quently, massive smoke is emitted through peat burning (Page *et al.*, 2002; Putra and Hayasaka, 2011, Toriyama *et al.*, 2014). Sharp peaks of R_d/R_g in 2002, 2006, and 2009 were caused by dense smoke from large-scale peat fires (Fig. 4).

The large R_d/R_g during El Niño drought suggests an increase in the atmospheric density of hygroscopic aerosol, which originated from smoke. The aerosol acts as cloud condensation nuclei and changes the size distribution of cloud particles (Kaufman and Fraser, 1997). Moreover, particles emitted through biomass burning and peat fires in Kalimantan, which had high sulfur content and high hygroscopicity, enlarged the

size distribution of cloud particles (Ikegami *et al.*, 2001) and consequently increased the reflection of solar radiation. Another effect of aerosol on cloud is a reduction of precipitation efficiency and increases the cloud lifetime (Ramanathan *et al.*, 2001). Thus, R_d/R_g remained large, above 0.7 for about two months in 2009 (Fig. 6). Precipitation in late October 2009 suggests the formation of persistent cloud particles (ABC; atmospheric brown cloud). The ABC is likely to increase aerosol's hygroscopicity and tends to grow with higher humidity (Fan *et al.*, 2010). After the onset of the rainy season, particle concentration returned to background values by rainfall washout (Heil *et al.*,

Fig. 6. Daily variations in the diffuse fraction (R_d/R_g) (a), global solar radiation (R_g) (b), precipitation (c), groundwater level (GWL) (d) and daytime vapor pressure deficit (VPD) (0900–1500 h) (e) for five months from July to November in 2009 (El Niño year) and 2010 (La Niña year) at DB site. The R_d/R_g , R_g , and VPD are shown as 5-day running means.

2007).

5. Conclusion

The diffuse fraction of global solar radiation in tropical peatland was controlled by seasonal variations in precipitation or cloud cover and smoke from peat fires and burning biomass, which are mostly due to human activities. If no fires occur, the diffuse fraction decreases in the dry season as precipitation decreases. In the late dry season, however, fires commonly occur and emit smoke, except for in La Niña years with no specific dry period. In particular, during El Niño droughts, massive smoke is frequently emitted from large-scale peat fires and densely shades the ground. As a result, the diffuse fraction becomes almost saturated. We parameterized a liner threshold model using field data and found that some parameters differed from those determined in Australia with drier climate. The model is applicable to estimate the diffuse fraction from widely measured global solar radiation for tropical peatland, in which the radiation environment is seriously disturbed.

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