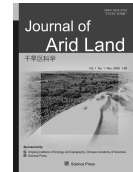




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Effects of cloud, atmospheric water vapor, and dust on photosynthetically active radiation and total solar radiation in a Mongolian grassland

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Abstract: Photosynthetically active radiation (PAR) is an important input parameter for estimating plant productivity due to its key role in the growth and development of plants. However, a worldwide routine network for systematic PAR measurements is not yet established, and PAR is often calculated as a constant fraction of total solar radiation (SR). Although the ratio of PAR to SR (PAR/SR) has been reported from many places, few studies have been performed for dry regions. The present study was therefore carried out in an arid region of Mongolia to obtain PAR/SR and examine its dependency on sky clearness (the clearness index), water vapor in the atmosphere and aeolian dust. Continuous measurements of PAR and SR were taken every one second using quantum and pyranometer sensors, respectively, and the readings were averaged and recorded at intervals of 30 minutes for a period of 12 months. The lowest monthly mean daily PAR/SR occurred in April (0.420), while the highest ratio was observed in July (0.459). Mean daily PAR/SR during plant growing season (May–August) was estimated to be 0.442, which could be useful for modeling plant productivity in the study area. The annual mean daily PAR/SR (0.435) was lower than the values reported in many previous studies. This difference could be explained with the regional variation in climate: i.e. drier climatic condition in the study area. PAR/SR was negatively correlated with the clearness index ($r = -0.36$, $P < 0.001$), but positively with atmospheric water vapor pressure ($r = 0.47$, $P < 0.001$). The average PAR/SR was significantly lower ($P = 0.02$) on the dusty days compared to the non-dust days. Water vapor in the atmosphere was shown to be the strongest factor in the variation of PAR/SR. This is the first study examining PAR/SR under a semi-arid condition in Mongolia.

Keywords: clearness index; dust storm; photosynthetically active radiation; total solar radiation; water vapor pressure

The photosynthetically active radiation (PAR) is the portion of total solar radiation (SR) in the waveband 0.4–0.7 μm , which is available for photosynthesis (McCree, 1972; Ross and Sulev, 2000). In general, plants use PAR as an energy source to convert CO_2 and water through photosynthesis into organic compounds (typically sugar, called glucose) which are then used to synthesize structural and metabolic energy required for plant growth and development, respiration, as well as stored vegetative products that result in plant biomass (Udo and Aro, 1999; Jacovides *et al.*, 2004). The accurate determination and clear understanding of the PAR component are required for many

applications, such as comprehensive studies of radiation climate, remote sensing of vegetation, radiation regimes of plant canopy and photosynthesis, an essential input in models estimating plant productivity, and carbon exchange between ecosystem and atmosphere (Pinker and Laszlo, 1992; Frouin and Pinker, 1995; Jacovides *et al.*, 2004; Wang *et al.*, 2005; Zhu *et al.*, 2010). A global routine network for measuring PAR is not yet established; however SR is often measured at meteorological stations (Gueymard, 1989; Ross and Sulev, 2000). Due to the limitation of PAR data, this

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parameter is often calculated indirectly based on its relationship with SR. Thus, by using such relationship, we could obtain PAR from the existing measured SR (Frouin and Pinker, 1995).

Various empirical relationships between PAR and SR have been derived when both PAR and SR measurements are available. Moon (1940) computed the spectral distribution of direct sunlight for sea level and suggested that PAR/SR was between 44% and 45% at places of low altitudes when the sun was more than 30° above the horizon, while Monteith (1973) suggested that the PAR can be taken as half of the total SR in the tropics as well as in temperate latitudes based on his measurement at Sutton Bonington (52°N, 50°W). However, the use of constant ratio of PAR to SR (PAR/SR) for different regions could lead to errors in the calculations of PAR (McCree, 1966, 1972; Pinker and Laszlo, 1992). As determined by McCree (1966), the average PAR/SR is 0.48, with the highest values occurring under cloud-covered sky. Also, other studies have found that PAR/SR was not constant, but varied according to location (Tsubo and Walker, 2005), season (Udo and Aro, 1999; Finch *et al.*, 2004), sky conditions (Rao, 1984; Papaioannou *et al.*, 1993), sky clearness, sky brightness, and atmospheric depth for the solar beam (Jacovides *et al.*, 2004), relative sunshine duration and water vapor pressure (Li *et al.*, 2010), altitude (Wang *et al.*, 2007), irradiance intensity (Britton and Dodd, 1976), day length (Szeicz, 1974; Britton and Dodd, 1976), dust and aerosol (Miskolczi *et al.*, 1997) and pyrogenic aerosols from biomass burning (Finch *et al.*, 2004). This spread of PAR/SR reported in the literature suggested that the relationship between PAR and SR needs to be calibrated according to local climatic conditions.

The atmospheric transmittance includes the attenuation of solar radiation by dust and aerosol scattering, and absorption by water, ozone and other atmospheric gases (Monteith and Unsworth, 1990; Jacovides *et al.*, 2005). Previous studies revealed that atmospheric parameters such as water vapor and cloud cover have the greatest influence on the PAR/SR, followed by dust and aerosol effects (Alados *et al.*, 1996), whereas ozone amount and ground albedo play a minor role in the variation of PAR/SR (Gonzalez and

Calbo, 2002). The ratio increases as sky condition changes from clear to overcast and with the increase of water vapor (Jacovides *et al.*, 2003). Also, dust is considered to be one of the major types of tropospheric aerosols, and constitutes an important parameter affecting visibility, perturbing the radiation energy balance of the earth-atmosphere system, and causing biological and ecological effects (Falkowski *et al.*, 1998; Kaufman *et al.*, 2002; Badarinath *et al.*, 2007; Maher *et al.*, 2010). An increase in dust concentration results in increased amount of solar energy absorbed, whereas smaller dust particles are more effective in scattering solar energy than larger particles (Waggoner *et al.*, 1981; Liao and Seinfeld, 1998).

PAR/SR has been reported from many places all over the world; however, few studies have been performed over dry regions (e.g. Al-Shooshan, 1997). The aim of this study is, therefore, to determine PAR/SR in an arid region, examine the temporal variations of PAR/SR, and investigate its dependence on sky conditions, atmospheric water vapor conditions, and dust storm.

1 Methods

1.1 Study area

The study area is located at Bayan Unjuul (47°02'37.2"N, 105°57'04.9"E) in the dry steppe zone of Mongolia (Shinoda *et al.*, 2010). The area is characterized by a semi-arid climate, defined on the basis of aridity index (UNEP, 1992), ranging between 0.2 and 0.5. It is a high altitude (1,200 m asl) site with good air transparency, strong solar radiation, and sparse vegetation cover. Summer season has long daylengths and sunshine duration, while winter has short daylengths but mostly clear days due to high pressure system. The natural aerosols increase in spring, with relation to dust storms. The vegetation of Bayan Unjuul is codominated by perennial grasses, forbs, and small shrubs (Shinoda *et al.*, 2010). Generally, the growing season for the Mongolian grasslands is very short (May–August) and it is limited by low temperature and precipitation (Shinoda *et al.*, 2007). The long-term (1995–2008) average air temperature and precipitation over the site are 16.9°C and 119 mm, respectively during the growing season.

1.2 Data collection

PAR and total SR (0.3–3.0 μm in wavelength) were recorded from July 2004 to June 2005 with a quantum sensor (LI190SZ, LI-COR Inc., Lincoln, Nebraska, USA) and a pyranometer sensor of the CNR1 net-radiometer (Kipp & Zonen B.V., Holland) mounted at 1.5 m height. Data were recorded every one second and the readings were averaged every 30 minutes in a data logger (Campbell Scientific, USA; CR10X). Prior to the measurement, the radiation sensors were calibrated.

1.3 Calculations

PAR was expressed in quantum flux ($\mu\text{mol}/(\text{m}^2\cdot\text{s})$), whereas SR was expressed in energy flux (W/m^2). Therefore, for comparison PAR photon flux was converted into its energy flux using the constant conversion factor of 0.2195 ($\text{W s}/\mu\text{mol}$) for a clear sky (Ross and Sulev, 2000).

Daily PAR/SR was calculated by dividing the daily sum of 30-min PAR with daily sum of 30-min SR. These daily values were then averaged over each month and season to get a mean monthly and seasonal daily PAR/SR.

The clearness index (the ratio of total SR to extraterrestrial SR) was used to characterize the sky conditions. In order to investigate the effect of sky conditions on PAR/SR in more detail, we divided the clearness index (K_T) into three equal classes ($K_T < 0.33$ for cloudy days; $0.33 \leq K_T \leq 0.67$ for partly cloudy days, and $K_T > 0.67$ for clear or nearly clear days). Daily extraterrestrial SR ($\text{MJ}/(\text{m}^2\cdot\text{day})$) on a horizontal surface was estimated from the solar constant ($0.082 \text{ MJ}/(\text{m}^2\cdot\text{min})$), the solar declination, and hours of solar radiation (Allen *et al.*, 1998).

Three-hourly water vapor pressure data and visual observations of dust storms were obtained from a meteorological station (450 m southeast of the observation site) operated by the Mongolian Institute of Meteorology and Hydrology. At the meteorological station, an observer recorded the duration and intensity of dust storms. In order to reveal the effect of dust storm, we examined the variations of SR, PAR, and PAR/SR between dust days (between sunrise and sunset hours) and non-dust days during the period from April to May in 2005, which is the most frequent dust storm period in Mongolia (Natsagdorj *et al.*, 2003; Jugder *et*

al., 2004). Here, a dust day was indicated as the day in which surface visibility is reduced to below 2,000 m by strong dust-raising wind. To compare daily radiation between dust and non-dust days, we excluded the cloudy days to avoid cloud effect. Also, it was noted that dust days were evenly distributed in April and May, thus dust and non-dust days didn't cause geometrical effect such as daylength and solar zenith angles.

2 Results and discussion

2.1 Monthly variations of extraterrestrial and total SR and PAR

Figure 1 shows the monthly extraterrestrial and total SR and PAR at the study area from July 2004 to June 2005. The radiation parameters show similar seasonal variations, with relative peaks in July (1,250 $\text{MJ}/(\text{m}^2\cdot\text{month})$ of extraterrestrial SR, 734 $\text{MJ}/(\text{m}^2\cdot\text{month})$ of total SR, and 336 $\text{MJ}/(\text{m}^2\cdot\text{month})$ of PAR) and the lowest values in December (293, 177, and 74 $\text{MJ}/(\text{m}^2\cdot\text{month})$, respectively). In comparison, monthly PAR was slightly lower in Ugtaal, Mongolia ($48^\circ 27' \text{N}$, $105^\circ 04' \text{E}$; 1,160 m asl), where it varied from 69 to 307 $\text{MJ}/(\text{m}^2\cdot\text{month})$ (Tugjsuren and Takamura, 2001), than in our study area ($47^\circ 02' 37.2'' \text{N}$, $105^\circ 57' 04.9'' \text{E}$; 1,200 m asl) due to differences in altitude and latitude. In addition, Ugtaal has more precipitation or greater humidity, resulting in relatively low radiation, compared with Bayan Unjuul. High correlations ($r > 0.96$) were found between the daily SR and PAR on the monthly and seasonal basis, thus allowing the estimation of one component by referring to the other.

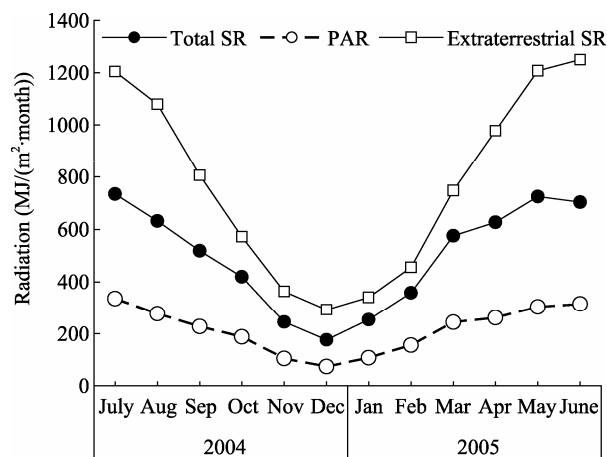


Fig. 1 Monthly extraterrestrial and total SR and total PAR in the study area from July 2004 to June 2005

2.2 Diurnal and seasonal changes in PAR/SR

The diurnal variations of the ratio were examined for each month (Fig. 2). The monthly mean diurnal variations of PAR/SR approached its highest or lowest values (sharp increases or decreases) during either sunrise or sunset hours for most months (January–April, October–December). As the ratio may be affected by

lower solar elevation, the data near sunset and sunrise hours should be excluded for hourly-based analysis. The figure further illustrates that during May and September the ratio did not show clear diurnal variations, whereas definite daily patterns are evident from June to August, especially for July, which is the wet-test month; the ratio was higher in the morning and

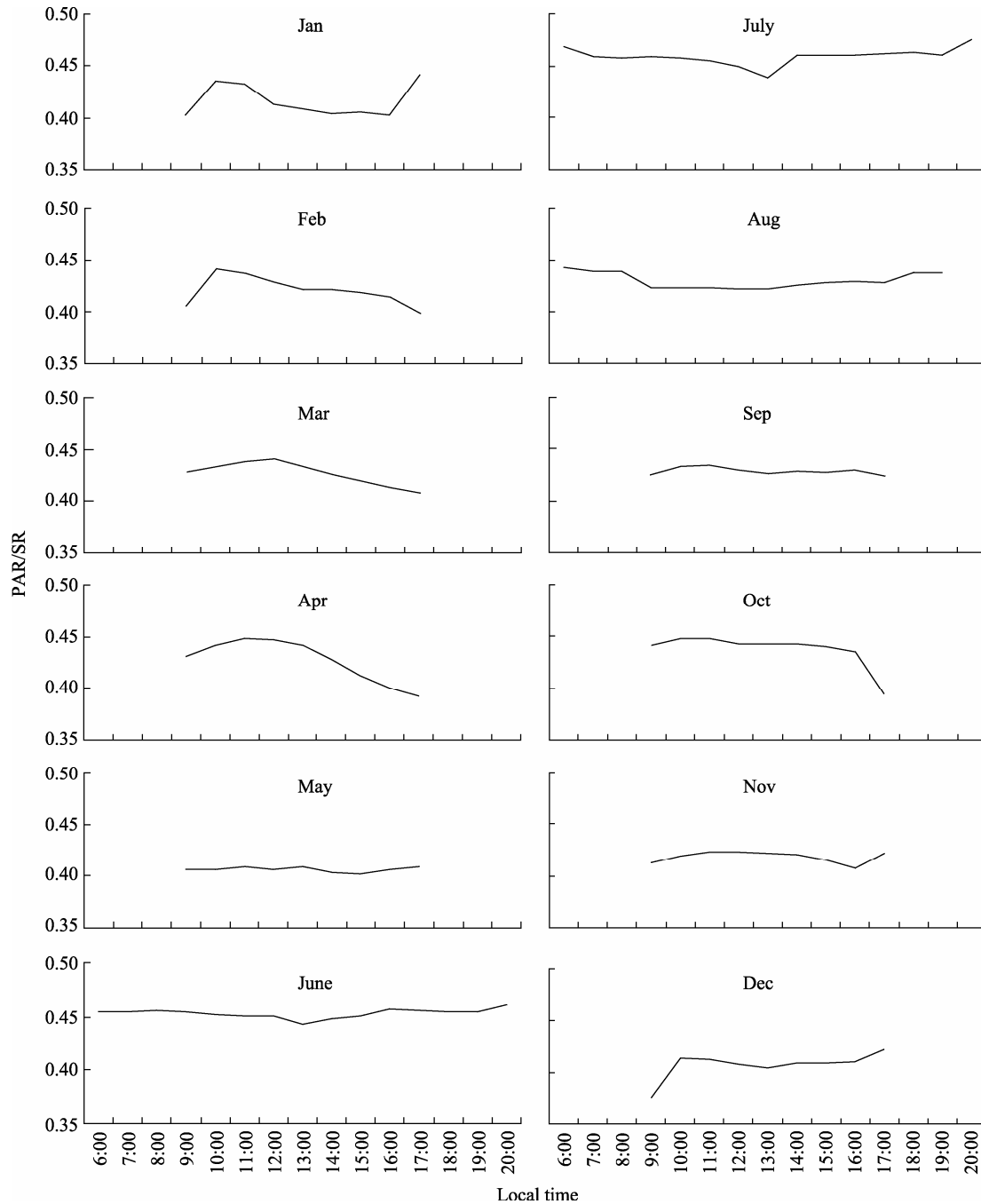


Fig. 2 Monthly mean diurnal variation of the PAR/SR in the study area

decreased gradually to its minimum at noon (when the sun is at its highest position in the sky, around 13:00 local time), and then increased in the afternoon. Similarly, in the previous studies PAR/SR reached its highest value during sunset and sunrise, and decreased to the lowest value around noon (13:00 local time in central Nigeria (Udo and Aro, 1999); 12:00–14:00 in Beijing (Hu *et al.*, 2007), and in Naeba Mountain, Japan (Wang *et al.*, 2007)). The similar diurnal variations have presented on the ratio of diffuse to global radiation (a decreasing trend from sunrise to noon and an increasing trend until sunset), as a consequence of enhanced diffuse component in relation to the global radiation at low sun elevation hours whereas the opposite trend occurred around noon (Kaskaoutis and Kambezidis, 2009).

Monthly mean of daily PAR/SR ranged from 0.420 in April to 0.459 in July, with the growing season average of 0.442 ± 0.021 and annual mean value of 0.435 ± 0.019 (Table 1). The annual mean of daily PAR/SR was lower than those in most previous studies, typically falling between 0.45 and 0.50, due to the region's dry climatic condition, whereas it was close to the value of 0.43 for Athens, Greece, 0.437 for Sweden, 0.439 for Tibet Plateau (April–October), and 0.440 for Fresno, USA and Aas, Norway. The range of monthly averaged daily PAR/SR (0.420–0.459) was similar to

that in Sweden (Rodskjer, 1983), Norway (Hansen, 1984), Greece (Papaioannou *et al.*, 1996), Nigeria (Udo and Aro, 1999) and Tibet (Zhang *et al.*, 2000).

2.3 Effect of cloud on PAR/SR

A significant inverse correlation ($r = -0.36$, $P < 0.001$) was found between the daily PAR/SR and clearness index. However, for very low values of clearness index (< 0.33 , cloudy sky) in the warm-wet season, PAR/SR tended to exhibit a more pronounced increase ($r = -0.71$, $P < 0.001$). According to the clearness index, 16 days were considered as cloudy, 141 days as partly cloudy, and 208 days clear or nearly clear (Table 2), indicating that one of the remarkable features of Mongolia is the dominance of clear days. PAR/SR increased from 0.430 on clear days to 0.439 and 0.456 on partly cloudy and cloudy days, respectively. The increases in PAR/SR under cloudy skies were mainly attributable to changes in the absorption spectra of the atmosphere. Clouds absorb more radiation in the infrared waveband than in PAR waveband. An increase in PAR/SR under cloudy conditions has also been reported in previous studies by Papaioannou *et al.* (1993), Hu *et al.* (2007), and Tsubo and Walker (2005). However, the effect of the clearness index on PAR/SR was negligible on a daily basis for Fresno, California, USA (Howell *et al.*, 1983).

Table 1 Monthly and seasonal averaged daily PAR/SR, clearness index (CI), atmospheric water vapor (WVP) and dust days (days of dust storms observed)

	PAR/SR		CI		WVP (hPa)		Dust days
	Average	St. Dev.	Average	St. Dev.	Average	St. Dev.	
July	0.459	0.016	0.57	0.13	11.86	2.38	-
August	0.439	0.016	0.59	0.15	9.61	2.55	-
September	0.438	0.012	0.64	0.12	6.07	2.20	2
October	0.449	0.012	0.73	0.09	3.28	0.97	1
November	0.429	0.014	0.68	0.14	1.92	0.66	1
December	0.423	0.013	0.63	0.10	1.32	0.52	-
January	0.425	0.017	0.75	0.07	0.95	0.33	-
February	0.437	0.015	0.79	0.07	0.65	0.25	-
March	0.427	0.016	0.77	0.07	2.18	0.80	-
April	0.420	0.016	0.64	0.13	3.31	0.95	11
May	0.421	0.010	0.64	0.11	4.68	1.47	7
June	0.448	0.020	0.56	0.16	8.32	1.76	2
Growing season (May–Aug)	0.442	0.021	0.59	0.14	8.62	3.34	9
Annual	0.435	0.019	0.66	0.14	4.54	3.83	24

Table 2 Number of days with cloudy, partly cloudy and clear sky, averaged PAR/SR with standard deviations for each classification, and correlation coefficient between PAR/SR and clearness index

	Clearness index			
	<0.33 (Cloudy)	0.33–0.67 (Partly cloudy)	>0.67 (Clear)	0–1
Number of days	16	141	208	365
PAR/SR	0.456±0.018	0.439±0.020	0.430±0.016	0.434±0.019
Correlation coefficient	−0.71*	−0.12	−0.22	−0.36*

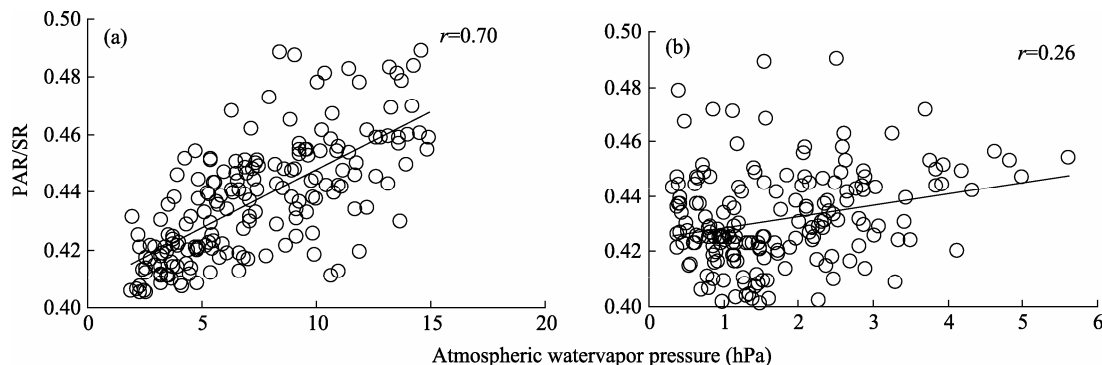
Note: * denotes significant correlations ($P<0.001$).

2.4 Effect of atmospheric water vapor on PAR/SR

A significant correlation was found between PAR/SR and water vapor pressure ($r=0.49$, $P<0.001$) for day time (08:00–17:00, local time). However, the correlation was stronger during April–September ($r=0.70$, $P<0.001$; Fig. 3a) than in the rest of the study period, i.e. October–March ($r=0.26$, $P<0.001$; Fig. 3b). McCree (1966) reported that during cloudy conditions the energy in the PAR region formed a greater part of short-wave radiation than on clear days. Similar seasonal variations in PAR/SR have been reported for Beijing (Hu *et al.*, 2007), where lower PAR/SR was observed during the dry season and higher PAR/SR occurred in the wet season. Thus, in Beijing, PAR/SR is controlled mainly by water vapor in the atmosphere (represented by relative humidity). Similarly, in the study area, it is likely that the increases in PAR/SR were found under cloudy and humid conditions, because the absorption of SR in the near infrared radiation (NIR) portion of the solar spectrum is greatly enhanced, whereas water vapor is almost transparent to PAR wavelengths. Thus, the decreasing of SR in the NIR range resulted in a higher PAR/SR ratio than in the spectral PAR (Alados *et al.*, 1996).

2.5 Visibility and PAR/SR

Remarkable decreases in the values of radiation components were found on dust days as compared with non-dust days (20.82 ± 2.89 MJ/(m²·day) of SR and 8.53 ± 1.17 MJ/(m²·day) of PAR on dust days; 22.68 ± 5.89 MJ/(m²·day) of SR and 9.5 ± 2.31 MJ/(m²·day) of PAR on non-dust days). Moreover, PAR/SR values were significantly lower ($P=0.02$) during dust days (0.41 ± 0.012) than on non-dust days (0.422 ± 0.016) for the dust frequent period in April and May. This effect reflected the fact that the solar radiation in the infrared waveband is more sensitive to the dust aerosol condition compared with PAR waveband (Jacovides and Karalis, 1996; Jacovides *et al.*, 2003). Diurnal variation of the PAR/SR in March and April revealed marked decreases in the afternoon hours (Fig. 2), which may be related with the increases of dust emission during daytime (the highest frequency occurs from 12:00 am to 18:00 pm) when the heating of the ground surface produces wind and unstable conditions in the air (Natsagdorj *et al.*, 2003). Similarly, heavy dust and aerosol loading tended to reduce solar radiation (Mikami, 2007) and PAR/SR in sub-sahel Africa and Cyprus (Miskolczi *et al.*, 1997; Jacovides *et al.*, 2004).

**Fig. 3** Relationships between daytime PAR/SR and atmospheric water vapor pressure during the periods of April–September (a) and October–March (b)

However, Harmattan dust is known to be non-wavelength selective attenuation of total solar radiation in the central Nigeria during winter solstice (Udo and Aro, 1999). A further understanding of the effect of dust aerosols on PAR/SR can be obtained with atmospheric radiation transfer models and satellite retrievals such as MODIS and TOMS Aerosol Index.

3 Conclusions

Based on the radiation data recorded at a Mongolian steppe, we analyzed the growing season PAR/SR (0.442 ± 0.021) and annual PAR/SR (0.435 ± 0.019) on the daily basis. We investigated the effects of sky condition on PAR/SR, and found that the value of the parameter increased as the clearness index decreased, i.e. sky conditions varied from clear to cloudy. Water vapor in the atmosphere was also found to cause significant changes in PAR/SR. PAR radiation transfers through the atmosphere, and reaches the Earth's surface almost unchanged under a clear sky. On the other

hand, NIR is affected greatly by the presence of water vapor in the lower troposphere where water vapor absorbs radiation in this range. These results are in agreement with previous studies and suggest that clearness index and water vapor pressure are the important variables in determining PAR/SR. Solar radiation decreased in dust days due to the scattering and absorption by dust aerosols. The effect of dust storms significantly decreased the PAR/SR. The paper is the first attempt to quantify PAR/SR for a dry region at high latitude; thus our ratio can be used to obtain important parameters of PAR for similar dry regions where SR data are available.

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