

## Effects of cloudiness change on net ecosystem exchange, light use efficiency, and water use efficiency in typical ecosystems of China

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### ABSTRACT

As a weather element, clouds can affect CO<sub>2</sub> exchange between terrestrial ecosystems and the atmosphere by altering environmental conditions, such as solar radiation received on the ground surface, temperature, and moisture. Based on the flux data measured at five typical ecosystems of China during mid-growing season (June–August) from 2003 to 2006, we analyzed the responses of net ecosystem exchange of carbon dioxide (NEE), light use efficiency (LUE, defined as Gross ecosystem photosynthesis (GEP)/Photosynthetically active radiation (PAR)), and water use efficiency (WUE, defined as GEP/Evapotranspiration (ET)) to the changes in cloudiness. The five ecological sites included Changbaishan temperate mixed forest (CBS), Dinghushan subtropical evergreen broad-leaved forest (DHS), Xishuangbanna tropical rainforest (XSBN), Inner Mongolia semi-arid *Leymus chinensis* steppe (NMG), and Haibei alpine frigid *Potentilla fruticosa* shrub (HB). Our analyses show that cloudy sky conditions with cloud index ( $k_t$ ) values between 0.4 and 0.6 increased NEE, LUE, and WUE of the ecosystems at CBS, DHS, NMG and HB from June to August. The LUE of tropical rainforest at XSBN was higher under cloudy than under clear sky conditions, but NEE and WUE did not decrease significantly under clear sky conditions from June to August. The increase in GEP with increasing diffuse radiation received by ecosystems under cloudy skies was the main reason that caused the increases in LUE and net carbon uptake in forest ecosystem at CBS, DHS, and alpine shrub ecosystem at HB, compared with clear skies. Moreover, for the ecosystem at CBS, DHS, and HB, when sky condition became from clear to cloudy, GEP increased and ET decreased with decreasing VPD, leading to the increase in WUE and NEE under cloudy sky conditions. The decrease in  $R_e$  with decreasing temperature and increase in GEP with decreasing VPD under cloudy skies led to the increase in LUE, WUE, and net carbon uptake of semi-arid steppe at NMG, compared to clear skies. These different responses among the five ecosystems are attributable to the differences in canopy characteristics and water conditions. From June to August, the peaks of the  $k_t$  frequency distribution in temperate ecosystems (e.g., CBS, NMG, and HB) were larger than 0.5, but they were smaller than 0.4 in subtropical/tropical forest ecosystems (e.g., DHS and XSBN). These results suggest that the pattern of cloudiness during the years from 2003 to 2006 in the five ecosystems was not the best condition for their net carbon uptake. This study highlights the importance of cloudiness factor in the prediction of net carbon absorption in the Asia monsoon region under climate change.

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### 1. Introduction

Solar radiation received on the ground surface drives photosynthesis (Urban et al., 2007; Baldocchi, 2008; Mercado et al., 2009) and evapotranspiration (ET) (Rocha et al., 2004) of terrestrial ecosystems, thus affecting the global carbon and water cycles. However,

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changes in cloudiness and aerosol content in the atmosphere can influence solar radiation received on the ground surface, balance of direct and diffuse components of the solar radiation received on the ground surface, and even regional climate (Gu et al., 2003; Niyogi et al., 2007; Urban et al., 2007). As a result, cloudiness change is a factor that affects carbon and water cycle of terrestrial ecosystems.

Many studies have shown that net ecosystem exchange of carbon dioxide (NEE) (Gu et al., 1999, 2003; Law et al., 2002; Urban et al., 2007), light use efficiency (LUE) (defined in the literatures as gross ecosystem photosynthesis (GEP)/Photosynthetically active radiation (PAR)) (Gu et al., 2002; Alton et al., 2007; Mercado et al., 2009), and water use efficiency (WUE) (defined in the literatures as NEE/ET) (Lamaud et al. 1997; Freedman et al., 2001; Rocha et al., 2004) of forest ecosystems increased on cloudy days compared to clear days. This phenomenon is mostly due to the effect of changes in cloudiness on a number of environmental variables. On cloudy days, global solar radiation received by an ecosystem decreases, while the diffuse radiation received by an ecosystem increases. The decrease in global solar radiation received by an ecosystem relieves the light saturation of canopy photosynthesis. The increasing diffuse radiation can easily reach shaded leaves to promote photosynthesis in a forest canopy with high leaf area index (LAI) (Gu et al., 2002; Farquhar and Roderick, 2003; Alton et al., 2007; Mercado et al., 2009). This increased canopy photosynthesis tends to enhance LUE under cloudy sky conditions rather than under clear sky conditions. Additionally, decreases in vapor pressure deficit (VPD) and temperature under cloudy sky conditions (Gu et al., 1999; Freedman et al., 2001) can increase canopy photosynthesis (Freedman et al., 2001) while reducing ecosystem respiration (Gu et al., 1999) and evapotranspiration (Law et al., 2002; Monson et al., 2002; Rocha et al., 2004) in forest ecosystems. As a result, NEE and WUE of forest ecosystems increase as well.

In short canopies with low LAI, such as grassland and shrub ecosystems, the penetration of solar radiation through the canopy is greater than in forest ecosystems (Letts et al., 2005), resulting in reduced or negligible effect of increase in diffuse radiation on NEE and LUE under cloudy sky conditions (Niyogi et al., 2004; Letts et al., 2005). These results suggest that the effects of clouds on NEE, LUE, and WUE vary with types of terrestrial ecosystems. Such varying responses may cause uncertainty in the evaluation of regional carbon budgets under changing climate conditions.

The eastern Asian monsoon makes the climate in Asia differ from those in Europe and North America. Temperature and precipitation exhibit apparent latitudinal gradients along the North-South Transect of Eastern China (NSTEC) (Yu et al., 2006). A vegetation sequence exists along the NSTEC from the north to the south including cold temperate coniferous forest, temperate mixed forests, warm temperate deciduous broadleaf forest, subtropical evergreen coniferous forest, evergreen broadleaf forest, and tropical rainforest (Yu et al., 2008b). The impact of continental climate and terrain results in apparent longitudinal gradients of precipitation and altitude from east to west in North China (Yu et al., 2006). This zone consists of temperate forest ecosystems, temperate steppe ecosystems, alpine shrub-meadow, and alpine meadow-steppe ecosystems distributed from east to west in North China (Yu et al., 2006; Fan et al., 2008). Forestland and grassland occupy approximately 18.2% and 40.0% of the total land area of China, respectively. Carbon storage and the function of carbon sink/source in these forest and grassland ecosystems make a significant contribution to the global carbon cycle (Fang et al., 2001; Fan et al., 2008). In the recent years, intensive research on dynamic variations of NEE and WUE at different spatiotemporal scales and their environmental controls have been conducted in different forest ecosystems along the NSTEC (Guan et al., 2006; Zhang et al., 2006; Yu et al., 2008a,b) and in different grassland ecosystems in China (Fu et al., 2006a,b; Kato et al., 2004; Hao et al., 2006; Li et al., 2006; Zhao et al., 2006; Hu et al.,

2008). These results indicate that the dynamic variations of NEE and WUE and their environmental controls vary with ecosystems because of the interactions between local climate and vegetation.

It is reported that global radiation was systematically reduced by 5–10% and even by 15–30% in certain areas of the Northern Hemisphere in the last 50 years (Stanhill and Cohen, 2001; Alton et al., 2007). Climate changes have decreased annual precipitation in North and Northeast China but increased it in the middle and lower Yangtze River basin since the 1990s (Wang et al., 2004; Ding et al., 2006). These changes in precipitation and cloudiness patterns can influence the global solar radiation received on the ground and other environmental factors (temperature, VPD, etc.) which all determine NEE, LUE, and WUE of different ecosystems in China. Therefore, the impacts of cloudiness pattern on carbon and water fluxes must be examined with respect to ecosystem differences before accurate evaluation can be made on carbon budgets and changes in the patterns of carbon sinks/sources in the eastern Asian monsoon region. Our previous study on the responses of NEE to changes in cloudiness in Changbaishan temperate mixed forest and Dinghushan subtropical evergreen broad-leaved forest demonstrated that cloudy skies favored increase in NEE (Zhang et al., 2010). However, a comprehensive study on the responses of NEE, LUE, and WUE to the changes in cloudiness based on broad types of forest and grassland ecosystems has not yet been performed.

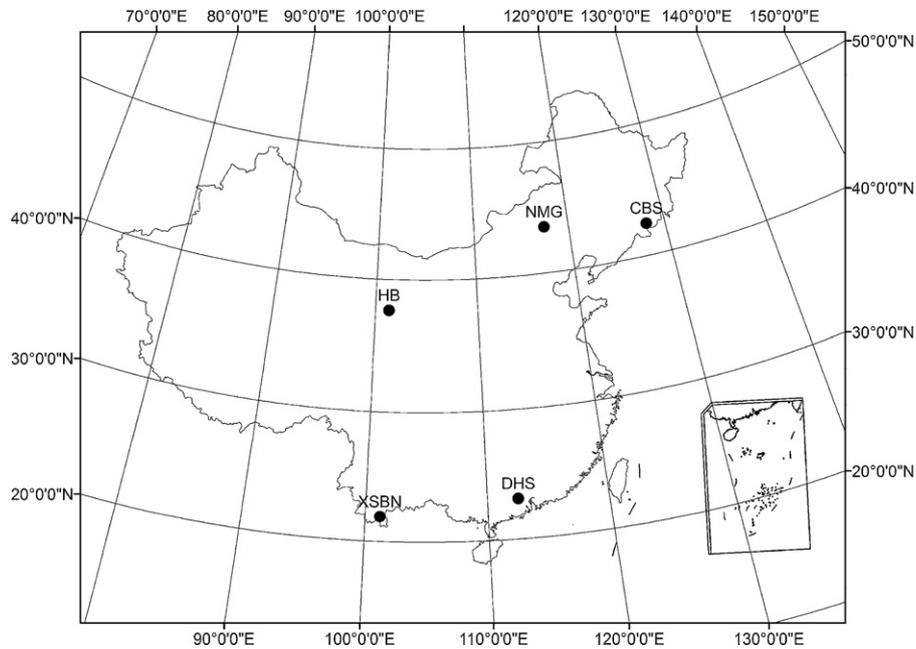
The objectives of this study were (1) to clarify the response of NEE, LUE, and WUE to the changes in cloudiness in forest ecosystems and grassland ecosystems of China, (2) to reveal the mechanisms that lead to the different changes in NEE, LUE, and WUE with cloudiness in different types of ecosystems, and (3) to determine whether the cloudiness level from 2003 to 2006 correlated to increases in NEE, LUE, and WUE in the above ecosystems. We hypothesized that the NEE, LUE, and WUE could increase under cloudy sky conditions in forest ecosystems but not in grassland ecosystems. This hypothesis was tested by analyzing the relationships between cloudiness and NEE, LUE, and WUE based on carbon and water flux data measured by eddy covariance (EC) technique and environmental variables data.

## 2. Materials and methods

### 2.1. Sites descriptions and measurements

#### 2.1.1. Sites descriptions

Field observations were performed at three forest ecosystems and two grassland ecosystems which belong to the Chinese Terrestrial Ecosystem Flux Observational Network (ChinaFLUX). The three forests consist of the Changbaishan temperate mixed forest (CBS), Dinghushan subtropical evergreen broad-leaved forest (DHS), and Xishuangbanna tropical rainforest (XSBN), which are located along the NSTEC. Specifically, CBS is located in the Jilin province of China and is subject to monsoon-influenced, temperate continental climate. Its growing season spans from May to September (Guan et al., 2006). DHS is located in the Guangdong province with a subtropical monsoon humid climate. It has a wet season from April to September and dry season from November to March (Zhang et al., 2006; Yu et al., 2008b). XSBN is located in the Yunnan province with a tropical monsoon climate. Its rainy season lasts from May through October, and its dry season lasts from November to April. The dry season is further divided into a cool-dry season from November to February, and a hot-dry season from March to April. Foggy days at XSBN are very common (mean annual 186 days) (Dou et al., 2006; Zhang et al., 2006). The two grassland ecosystems are the Inner Mongolia semi-arid *L. chinensis* steppe (NMG) which is C3 grass land, and Haibei alpine frigid *P. fruticosa* shrub (HB). NMG is located in the Xilin River Basin, Inner Mongolia Autonomous Region of China with a temperate semiarid continental climate. Its grow-



**Fig. 1.** Locations of Changbaishan temperate mixed forest site (CBS), Dinghushan subtropical evergreen broad-leaved forest site (DHS), Xishuangbanna tropical rainforest site (XSBN), Inner Mongolia semi-arid steppe site (NMG), and Haibei alpine frigid shrub site (HB).

ing season lasts from late April to early October. HB is located in the northeast of the Qinhai-Tibet Plateau with a plateau continental climate, which is characterized by lengthy cold winters and very short warm summers. Being situated in a frigid highland, HB receives strong solar radiation, with a mean annual global solar radiation of up to  $6000\text{--}7000\text{ MJ m}^{-2}$  (Fu et al., 2006b). The locations of five sites are shown in Fig. 1, and a detailed description of the five sites are provided in Table 1.

### 2.1.2. Experimental measurements

As part of the ChinaFLUX network research, the measurement of the eddy fluxes of carbon dioxide and water vapor began at the five sites in late 2002 or early 2003. The eddy covariance (EC) system consists of an open-path infrared gas analyzer (Model LI-7500, LICOR Inc., Lincoln, NE, USA) and a 3-D sonic anemometer (Model CSAT3, Campbell Scientific Inc., Logan, UT, USA). The signals of the instruments were recorded at 10 Hz by a CR5000 datalogger (Model CR5000, Campbell Scientific Inc.) and then block-averaged over 30-

min intervals for analyses and archiving (Guan et al., 2006; Fu et al., 2006b; Zhang et al., 2006; Yu et al., 2008b).

Routine meteorological variables were measured simultaneously with the eddy fluxes at each site. Air humidity and air temperature were measured with shielded and aspirated probes (HMP45C, Vaisala, Helsinki, Finland) at different heights. Global radiation and net radiation were recorded with radiometers (CM11 and CNR-1, Kipp & Zonen, Delft, The Netherlands). Photosynthetically active radiation (PAR) above the canopy was measured with a quantum sensor (LI-190Sb, LiCor Inc., USA). Precipitation was recorded with a rain gauge (RainGauge 52203, Young, Traverse City, MI, USA). Soil temperature and soil water content were monitored using thermocouple probes (105T in forest sites, 107L in grassland sites, Thermocouple Scientific Inc.) and water content reflectometers (Model CS616 in forest sites and Model CS615L in grassland forest, Campbell Scientific Inc.), respectively. All meteorological measurements were recorded at 30-min intervals with dataloggers (Model CR10X & CR23X, Campbell Scientific Inc.) (Guan et al., 2006; Fu et al.,

**Table 1**  
Site descriptions.

Site	CBS	DHS	XSBN	NMG	HB
Ecosystem type	Temperate forest	Subtropical forest	Tropical rain forest	Semi-arid steppe	Alpine frigid shrub
Location	42°24'N, 128°05'E	23°10'N, 112°34'E	21°30'N, 101°21'E	43°53'N, 117°27'E	37°29'N, 101°20'E
Elevation (m)	738	300	750	1189	3300
Mean annual temperature (°C)	3.6	21.0	21.5	-0.4	-1.7
Annual precipitation (mm)	695	1956	1493	350.9	600
Predominant species	<i>Pinus koraiensis</i> , <i>Tilia amurensis</i> , <i>Quercus mongolica</i> , <i>Fraxinus mandshurica</i> , <i>Acer miono</i>	<i>Schima superba</i> , <i>Castanopsis chinensi</i> , <i>Pinus massoniana</i>	<i>Pometia tomentosa</i> , <i>Terminalia myriocarpa</i> , <i>Barringtonia macrostachya</i>	<i>Leymus Chinensis</i> , <i>Achnatherum sibiricum</i> , <i>Stipa gigantean</i> , <i>Agropyron michnoi</i>	<i>Potentilla fruticosa L.</i> , <i>Kobresia humilis</i> , <i>Poa Annuu</i> , <i>Festuca rubra</i>
Canopy Height (m)	26	20	36	0.45	0.6
Leaf area index ( $\text{m}^2\text{ m}^{-2}$ )	6.1 (maximum in grown season)	4.0	3.0	1.5 (maximum in grown season)	2.8 (maximum in grown season)
Height of OPEC (m) <sup>a</sup>	40	27	48.8	2.2	2.2
Height of radiometer (m) <sup>a</sup>	32	36	48.8	1.2	1.2
Profiles of air temperature and humidity (m) <sup>a</sup>	2.5, 8, 22, 26, 32, 50, 60	4, 9, 15, 21, 27, 31, 36	4.2, 16.3, 26.2, 36.5, 42, 48.8, 70	1.1, 2.2	1.1, 2.2
Depth of soil moisture (cm) <sup>a</sup>	5, 20, 50	5, 20, 40	5, 20, 40	5, 20, 40	20, 40

<sup>a</sup> Height and depth at the location of the sensors mounted.

2006b; Zhang et al., 2006; Yu et al., 2008b). Detailed information on the meteorological variables is summarized in Table 1.

The LAI of temperate ecosystem, such as CBS, NMG, and HB, changed with season. In the study, we used only the data measured during the periods of relatively stable LAI each year from 2003 to 2006 in order to eliminate the potential effect of changing LAI. The LAI of temperate ecosystems remain stable in the mid-growing season (June to August in CBS and NMG, and July to August in HB). DHS and XSBN are evergreen forest ecosystems, and their LAI did not vary much seasonally and intra-seasonally. However, we still used the data measured from June to August in DHS and XSBN for comparison with the three temperate ecosystems.

## 2.2. Data processing

### 2.2.1. Flux data processing

The flux data processing included: (1) 3D coordinate rotation was applied to force the average vertical wind speed to zero and to align the horizontal wind to mean wind direction (Baldocchi et al., 2000; Wilczak et al., 2001), (2) flux data was corrected according the variation of air density caused by transfer of heat and water vapor (Webb et al., 1980), (3) the storage below EC height was corrected for forest sites (Hollinger et al., 1994; Carrara et al., 2003), and (4) the outlier data were filtered and data gaps were filled by using the look-up table method and mean diurnal variation (MDV) (Falge et al., 2001; Guan et al., 2006; Zhang et al., 2006). Then we got continuous 30 min flux data.

In this study, the sign of NEE was negative when CO<sub>2</sub> was transported from the atmosphere to the ecosystem and positive for the opposite case.

### 2.2.2. Flux partitioning

Gross ecosystem photosynthesis (GEP) was calculated using the following equation:

$$\text{GEP} = R_e - \text{NEE}. \quad (1)$$

NEE was obtained directly from the EC measurement. Ecosystem respiration ( $R_e$ ) of the five sites was estimated using the Lloyd–Taylor equation (1994) (Fu et al., 2006a,b; Yu et al., 2008a). The nighttime NEE data under turbulent conditions were used to establish  $R_e$ -temperature response relationship Eq. (2):

$$R_e = R_{\text{ref}} e^{E_0(1/(T_{\text{ref}}-T_0)-1/(T-T_0))} \quad (2)$$

where  $T$  is air temperature or soil temperature (°C). For CBS, XSBN, NMG and HB, soil temperature at 5 cm was used, while air temperature at 4 m above ground was used for DHS (Yu et al., 2005; Fu et al., 2006a,b), for better regressions (i.e. higher  $R^2$  value) relative to the use of soil temperature (Yu et al., 2005; Yu et al., 2008b). In the equation,  $R_{\text{ref}}$  represents the ecosystem respiration rate at a reference temperature ( $T_{\text{ref}}$ , 10 °C),  $E_0$  is the parameter that essentially determines the temperature sensitivity of ecosystem respiration and  $T_0$  is a constant, set at -46.02 °C. Eq. (2) was also used to estimate daytime  $R_e$ .

### 2.2.3. Ecosystem light use efficiency

In the study, LUE (mmolCO<sub>2</sub> mol<sup>-1</sup> quantum) was defined as the ratio of GEP (mgCO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>) to incident PAR (μmol quantum m<sup>-2</sup> s<sup>-1</sup>),

$$\text{LUE} = \frac{\text{GEP}}{\text{PAR}} \cdot \frac{10^6}{44} \quad (3)$$

where 10<sup>6</sup>/44 is unit conversion coefficient. The definition of LUE denotes that ecosystem absorbed carbon dioxide using per unit incident PAR.

### 2.2.4. Ecosystem water use efficiency

WUE was defined as the ratio of GEP to ET (gH<sub>2</sub>O m<sup>-2</sup> s<sup>-1</sup>), where ET was measured directly by EC technique,

$$\text{WUE} = \frac{\text{GEP}}{\text{ET}} \quad (4)$$

The definition of WUE (mgCO<sub>2</sub> g<sup>-1</sup>H<sub>2</sub>O) reflects trade-off between water loss and carbon dioxide gain and quantifies the coupling between carbon and water cycles at ecosystem level (Yu et al., 2004).

### 2.2.5. Clearness index

Cloudiness is used in a very general sense referring to the presence, quality, and quantity of clouds in the sky in this study. Because of a lack of continuous measurements of cloudiness at the five sites, we used a clearness index ( $k_t$ ) to describe the changes in cloudiness. The  $k_t$  is defined as the ratio of global solar radiation ( $S$ , W m<sup>-2</sup>) received at the Earth's surface to the extraterrestrial irradiance at a plane parallel to the Earth's surface ( $S_e$ , W m<sup>-2</sup>) (Gu et al., 1999):

$$k_t = \frac{S}{S_e} \quad (5)$$

$$S_e = S_{\text{sc}} \left[ 1 + 0.033 \cos \left( \frac{360t_d}{365} \right) \right] \sin \beta \quad (6)$$

$$\sin \beta = \sin \varphi \cdot \sin \delta + \cos \varphi \cdot \cos \delta \cdot \cos \omega \quad (7)$$

where  $S_{\text{sc}}$  is the solar constant (1370 W m<sup>-2</sup>),  $t_d$  is the day of year,  $\beta$  is the solar elevation angle,  $\varphi$  is degree of latitude,  $\delta$  is declination of the sun, and  $\omega$  is time angle. The  $k_t$  reflects not only sky conditions but also the degree of influence of cloudiness on solar radiation received on the ground surface. For a given solar elevation angle, a value of  $k_t$  approaching zero indicates an increase in cloud thickness or weak solar radiation received on the ground surface. On the contrary, a value of  $k_t$  approaching 1 indicates a clear sky or strong solar radiation received on the ground surface (Gu et al., 1999).

We analyzed the relationship between  $k_t$  and NEE to reveal the effect of change in cloudiness on net carbon uptake of the five selected ecosystems. The data observed in the highest interval of solar elevation angles were chosen to eliminate the effect of change in solar elevation angles on the response of NEE to  $k_t$ . The highest intervals of solar elevation angle are different among the five ecosystems because of their different geographic locations. The highest interval of solar elevation angle is 60–70° in CBS and NMG, 80–90° in DHS, 75–85° in XSBN, and 65–75° in HB. We divided  $k_t$  into intervals of 0.1 and computed mean NEE for each interval for the five ecosystems. A Student's t-test was used to compare the mean NEE within smaller  $k_t$  intervals ( $k_t > 0.3$ ) with that under clear skies (CBS:  $k_t = 0.7$ – $0.8$ , DHS:  $k_t = 0.7$ – $0.8$ , XSBN:  $k_t = 0.6$ – $0.7$ , NMG and HB:  $k_t = 0.8$ – $0.9$ ) in order to identify the significant changes in NEE under different cloudiness conditions.

### 2.2.6. Defining diffuse PAR

For a given solar elevation angle, the diffuse components of the solar radiation received by ecosystem could change with cloudiness (Gu et al., 2002; Urban et al., 2007). However, the diffuse PAR was not measured at the two sites. Therefore, we used the relationship between  $k_t$  and  $\beta$  to calculate diffuse PAR as described in Gu et al. (1999).

## 2.3. Statistical analysis

The relationships between different variables were fitted with linear and non-linear equations. All analyses were made using the Origin package v. 7.5 (OriginLab corporation, Northampton,

MA, USA). Statistical significant differences were set with  $P < 0.05$  ( $\alpha = 0.05$ ) unless otherwise stated.

### 3. Results

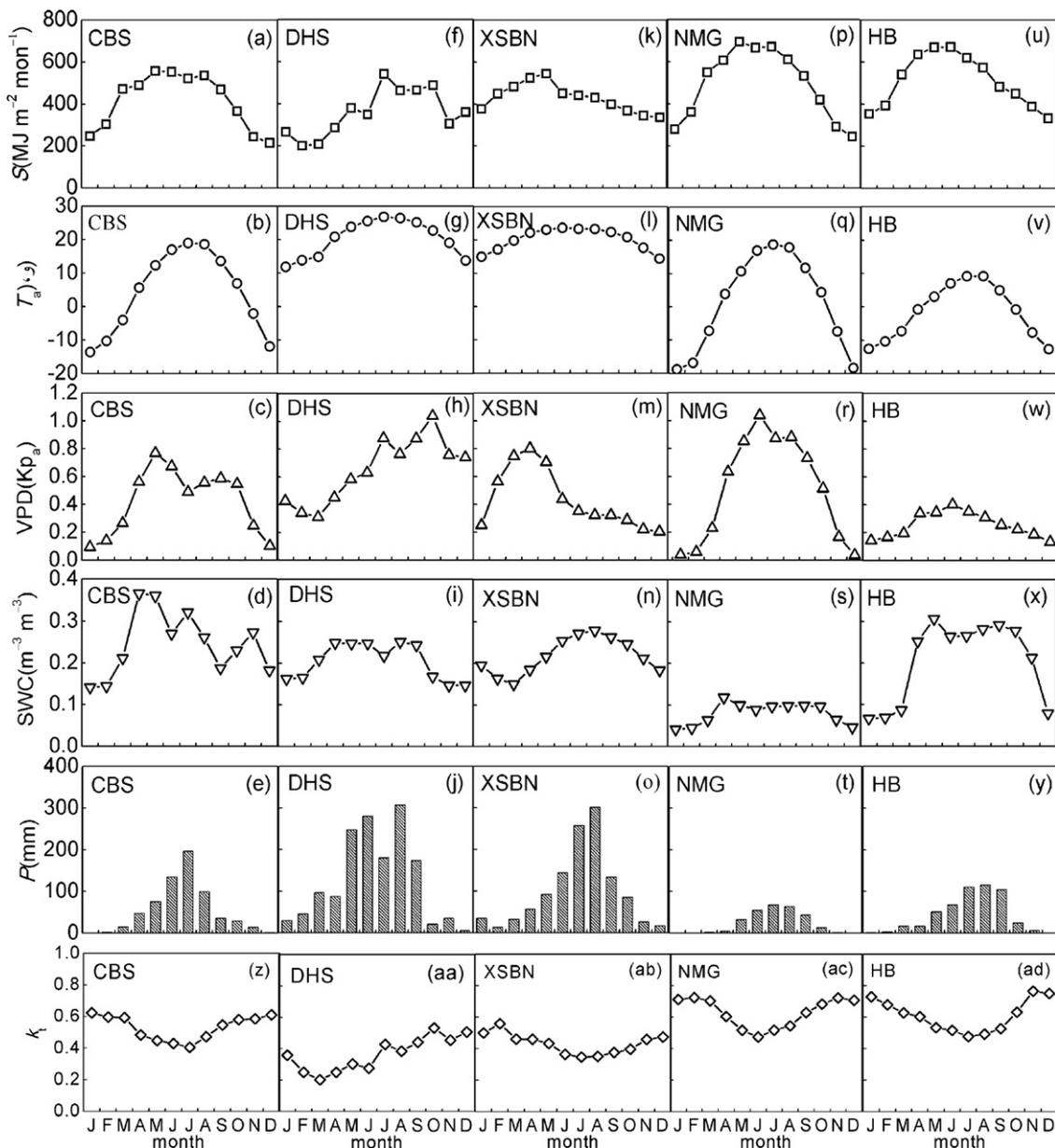
#### 3.1. Seasonal variation of environmental variables

Fig. 2 shows the seasonal variations of meteorological variables of the five ecosystems from 2003 to 2006. Solar radiation received by the ecosystem ( $S$ ) was higher at CBS, NMG, and HB than at DHS and XSBN during the growing season (May to August) (Fig. 2a, f, k, p, and u). Among them, NMG and HB sites received the most solar radiation during the mid-growing season (Fig. 2p and u). The maximum value of  $S$  occurred in May at CBS, NMG, HB and XSBN (Fig. 2a, k, p, and u), and in July at DHS (Fig. 2f).

Air temperature ( $T_a$ ) was higher at DHS and XSBN than at CBS, NMG, and HB.  $T_a$  of the five sites reached its maximum during the mid-growing season (Fig. 2b, g, l, q, and v). Except for XSBN,  $T_a$  of

other four sites peaked in July (Fig. 2b, g, q, and v).  $T_a$  of XSBN was highest in June (Fig. 2l).  $T_a$  of HB and DHS were lowest and highest, respectively, among the five sites during the mid-growing season (Fig. 2g and v).

Precipitation ( $P$ ) was greater at DHS and XSBN than at CBS, NMG and HB.  $P$  at the five sites reached its maximum during the mid-growing season (Fig. 2e, j, o, t, and y). The total  $P$  from June to August was 431 mm, 769 mm, 703 mm, 188 mm and 294 mm at CBS, DHS, XSBN, NMG, and HB, respectively. The  $P$  at NMG during the mid-growing season was least among the five sites (Fig. 2t). SWC was in agreement with  $P$  at DHS and XSBN (Fig. 2i and n). The SWC of DHS and XSBN reached its maximum in August in which  $P$  of the two sites was greatest. However, SWC of the three temperate ecosystems, CBS, NMG, and HB, was affected by not only  $P$  but also spring thaw. The SWC of the three sites was highest in April or May (Fig. 2d, s, and x). The SWC of NMG was smallest among the five sites during the mid-growing season (Fig. 2s).



**Fig. 2.** The seasonal variations of monthly cumulative global solar radiation ( $S$ ), monthly mean air temperature ( $T_a$ ), vapor pressure deficit (VPD), monthly mean soil water content (SWC, 5 cm depth at CBS, DHS, XSBN, and NMG, and 20-cm depth at HB), monthly cumulative precipitation ( $P$ ), and monthly mean clearness index ( $k_t$ ) for solar elevation angle  $>20^\circ$  at the five sites.

Vapor press deficit (VPD) was affected by both temperature and precipitation at the five sites. The VPD of the five sites reached the maximum at high temperature and low precipitation (Fig. 2c, h, m, r, and w). The VPD of the forest sites (XSBN, CBS, and DHS) was highest in April, May, and October, respectively (Fig. 2c, h, and m). The VPD of grassland sites (NMG and HB) was highest in June (Fig. 2r and w). The NMG site exhibited the highest VPD among the five sites during the mid-growing season (Fig. 2r).

Clearness index ( $k_t$ ) was greater at NMG, HB, and CBS than at DHS and XSBN (Fig. 2z, aa, ab, ac, and ad), especially during the mid-growing season. The  $k_t$  values of temperate ecosystems (CBS, NMG, and HB) were lowest during the mid-growing season (Fig. 2z, ac, and ad). The  $k_t$  values of subtropical forest at DHS and tropical rainforest at XSBN reached the maximum in October and February, respectively (Fig. 2ab and ac). The results indicate that clear days were more at NMG, HB, and CBS than at DHS and XSBN. Except at XSBN, cloudy days at all sites were more in the mid-growing season than in other seasons.

Overall, seasonal variations of environmental variables indicate that CBS had good light, temperature, and water conditions in the mid-growing season. DHS and XSBN were relatively poor in light resource, although they had good temperature and water conditions during the same period. HB was plentiful in light and water resources, but temperature was low during the mid-growing season. NMG had good light and temperature conditions, but it was

driest due to drought stress among the five sites during the mid-growing season.

### 3.2. Frequency distribution of clearness index value in the five ecosystems

The seasonal variation of clearness index ( $k_t$ ) (Fig. 2z, aa, ab, ac, and ad) shows the seasonal dynamics of skies conditions but not the frequency distribution of  $k_t$  or real temporal patterns of cloudiness at the five sites in the mid-growing seasons. Fig. 3 shows histograms of  $k_t$  values for solar elevation angles larger than  $20^\circ$  in the five ecosystems in the mid-growing seasons from 2003 to 2006. Although they had inter-annual variations due to the dynamics of climate, the cloudiness patterns had common characteristics among the five sites. The  $k_t$  values at CBS had largest frequency around 0.6 each year from 2003 to 2006 (Fig. 3a, b, and d), except for 2005, in which the largest frequency occurred between 0.2 and 0.4 (Fig. 3c) because of the effect of plentiful precipitation in the growing season. The peaks of  $k_t$  frequency at NMG and HB occurred around 0.7 and 0.8, respectively, in the mid-growing seasons from 2003 to 2006 (Fig. 3m–t). The  $k_t$  peak value (0.6–0.8) in these three temperate ecosystems were all larger than 0.5. The peak of  $k_t$  frequency for DHS was around 0.6 in 2003 and in 2004, but less than 0.2 in 2005 and in 2006 (Fig. 3e and f). The  $k_t$  frequency at XSBN maximized at about 0.3 in the 4 years (Fig. 3i–l). The highest  $k_t$  fre-

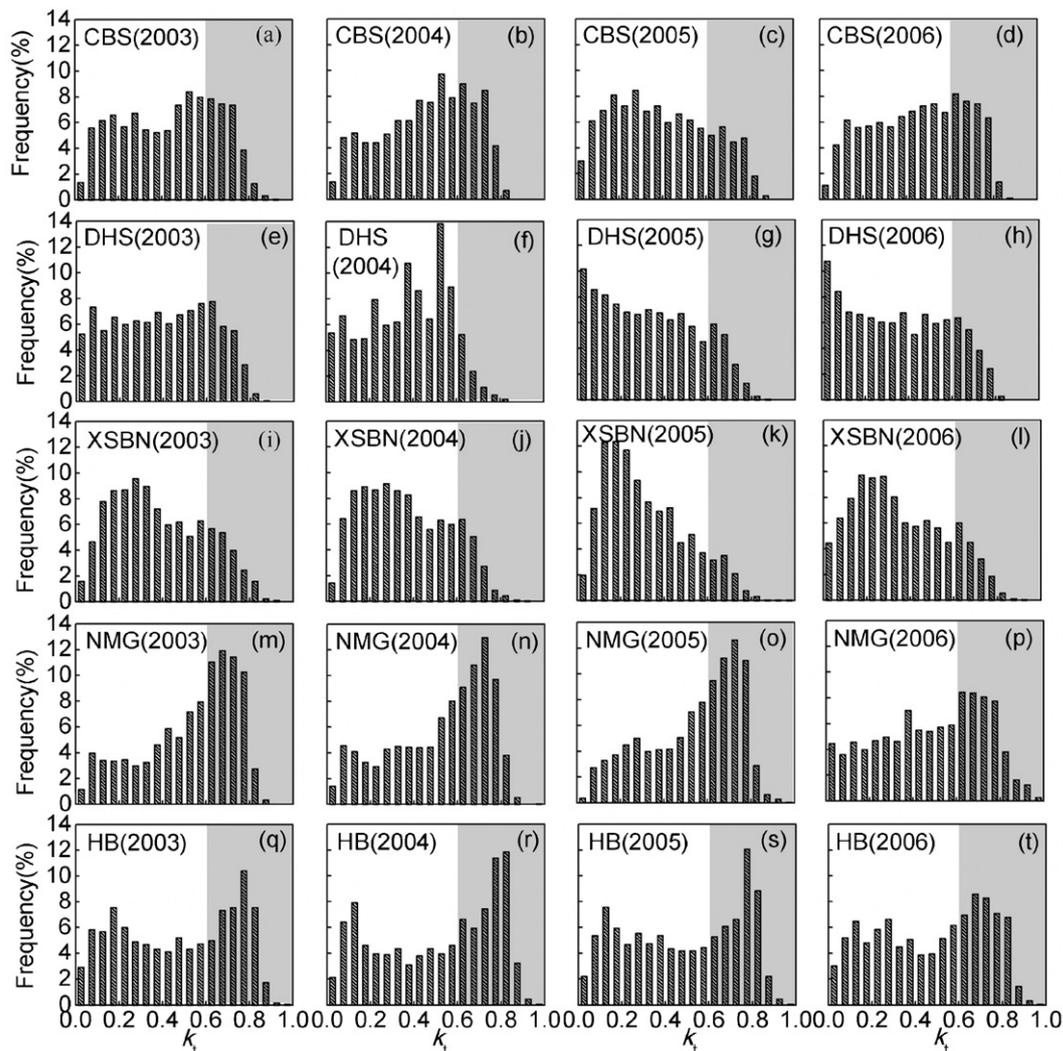
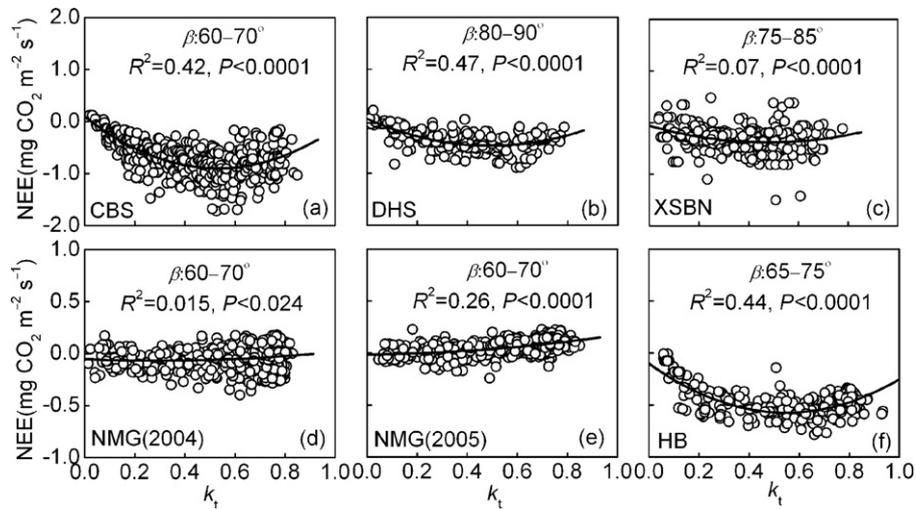


Fig. 3. Histograms of the clearness index ( $k_t$ ) value for solar elevation angle  $>20^\circ$  at the five sites during the mid-growing seasons from 2003 to 2006. The gray areas represent the range of clear skies.



**Fig. 4.** Relationship between NEE and the clearness index ( $k_t$ ) for the highest interval of solar elevation angles at CBS (a), DHS (b), XSBN (c), and HB (f) during the mid-growing season in 2005 and at NMG (d–e) during the mid-growing seasons in 2004 and 2005.

quency at DHS and XSBN in the mid-growing season occurred at the value of  $k_t$  lower than 0.4 (Fig. 3e–f) due mostly to the effect of high precipitation.

3.3. Change of NEE with clearness index

Similar results about changes of NEE, LUE, and WUE with clearness index were obtained for CBS, DHS, XSBN, and HB during the mid-growing seasons from 2003 to 2006. We thus present only the results of 2005. For the NMG site, the result of 2004 was included for comparison because this site had undergone drought stress during the growing season of 2005.

Fig. 4 shows the impact of cloudiness on the NEE of the five ecosystems. The NEE changed with  $k_t$  in a conic relationship (Table 2) at CBS, DHS, and HB during the mid-growing season (Fig. 4a, b, and f). The regression coefficients of the conic equations are provided in Table 2. When the value of  $k_t$  ranged between 0.4 and 0.6, the NEE reached its maximum at these three sites. When the value of  $k_t$  exceeded 0.6, the NEE decreased (Fig. 4a, b, and f). These results indicate that net carbon uptakes of the three ecosystems were highest under partly cloudy skies. For the XSBN site, the conic relationship between NEE and  $k_t$  was weak during the mid-growing season (Fig. 4c). The NEE of this ecosystem did not decrease significantly when the value of  $k_t$  exceeded 0.6 (Fig. 4c). This result implies that clear skies did not restrain net carbon uptake in this tropical rain forest ecosystem as much as in the temperate forest ecosystem of CBS and in the subtropical forest ecosystem of DHS during the mid-growing season. The change in NEE with  $k_t$  was different between wet and dry years in the semi-arid steppe ecosystem at NMG. In 2004 (the wet year), the NEE of this ecosystem did not markedly change with  $k_t$  (Fig. 4d), but in 2005 (the dry year)

the ecosystem exhibited a net carbon emission when  $k_t$  exceeded 0.6 (Fig. 4e).

Table 3 shows the optimal clearness index value for maximum NEE at CBS, DHS, and HB in the mid-growing season. The optimal clearness index was not available for the XSBN and NMG sites because of the poor conic relationship between NEE and  $k_t$ . The optimal clearness index value showed inter-annual variations. The mean value was about 0.5 at CBS, DHS, and HB (Table 3), suggesting that partly cloudy skies or thin clouds were favorable for net carbon uptake in these three ecosystems.

To verify the enhancement of NEE under cloudy skies, we compared the mean NEE within every  $k_t$  interval of 0.1 under cloudy skies ( $k_t > 0.3$ ) to the mean NEE within the  $k_t$  interval of 0.1 under clear skies (CBS:  $k_t = 0.7-0.8$ , DHS:  $k_t = 0.7-0.8$ , XSBN:  $k_t = 0.7-0.8$ , NMG and HB:  $k_t = 0.8-0.9$ ) in the mid-growing seasons from 2003 to 2006. Expect at XSBN, significant differences in NEE existed at all the sites between the conditions of cloudy skies and clear skies (Table 4). The results indicated that the partly cloudy skies favored net carbon uptake of temperate ecosystems (e.g. CBS, NMG, and HB) and subtropical ecosystems (e.g. DHS).

3.4. Change in LUE with clearness index

Fig. 5 shows the changes in LUE with  $k_t$ . The change tendency was similar among the five ecosystems. LUE decreased exponentially with increasing  $k_t$  (Fig. 5). The regression coefficients for the associated exponential equations are presented in Table 5. The LUE at CBS, DHS, XSBN, and HB was larger than at NMG. The decrease in LUE at the three forest ecosystems was more obvious than that at the two grassland ecosystems (Fig. 5b). At NMG, the drought stress in 2005 did not affect the relationship between LUE and  $k_t$  compared to the wet year of 2004 (Fig. 5). Overall, our observation indicates that ecosystem LUE at the five sites tended to maximize under overcast skies conditions.

**Table 2**

Regression coefficients of the conic equation ( $NEE^a = a k_t^2 + b k_t + c$ ) at CBS, DHS, XSBN, and HB during the mid-growing season in 2005 and at NMG during the mid-growing seasons in 2004 and 2005.

Site	a	b	c	R <sup>2</sup>
CBS (2005)	3.50	-3.73	0.09	0.42
DHS (2005)	2.13	-2.10	0.05	0.47
XSBN (2005)	1.41	-1.35	-0.06	0.07
NMG (2004)	0.17	-0.10	-0.05	0.015
NMG (2005)	0.16	0.03	-0.01	0.26
HB (2005)	1.58	-1.73	-0.10	0.44

<sup>a</sup> Unit of NEE is  $\text{mgCO}_2 \text{ m}^{-2} \text{ s}^{-1}$ .

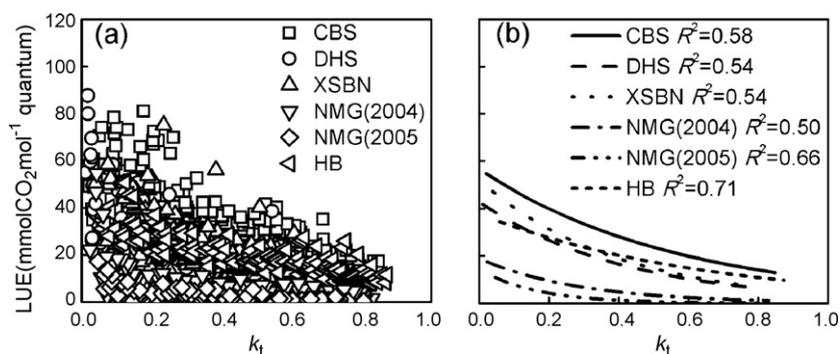
**Table 3**

The optimal clearness index at the five sites during the mid-growing seasons from 2003 to 2006.

Site	CBS	DHS	XSBN	NMG	HB
2003	0.49	0.49	-	-	0.53
2004	0.48	0.35	-	-	0.55
2005	0.53	0.49	-	-	0.55
2006	0.53	0.54	-	-	0.58
Average	0.51	0.47	-	-	0.55

**Table 4**  
Comparisons of mean NEE ( $\text{mgCO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) for  $k_t$  intervals greater than 0.3 against mean NEE under clear sky (CBS:  $k_t = 0.7\text{--}0.8$ ; DHS:  $k_t = 0.7\text{--}0.8$ ; XSBN:  $k_t = 0.7\text{--}0.8$ ; NMG and HB:  $k_t = 0.8\text{--}0.9$ ) at the five sites.  $t$  is student's statistic,  $P$  significance of  $t$  at 0.05 level, NS means  $t$  is not significant.

Sites	Interval of $k_t$	NEE mean	NEE SD	$t$ (Equal variance assumed)	$t$ (Equal variance not assumed)	$P$ (Equal variance assumed)	$P$ (Equal variance not assumed)
CBS	0.3–0.4	–0.749	0.235	7.307	7.251	0.000	0.000
	0.4–0.5	–0.794	0.247	9.598	9.536	0.000	0.000
	0.5–0.6	–0.810	0.274	10.197	10.287	0.000	0.000
	0.6–0.7	–0.773	0.273	8.410	8.523	0.005	0.004
	0.7–0.8	–0.606	0.218	–	–	–	–
	>0.8	–0.707	0.286	1.494	1.158	0.136 (NS)	0.273 (NS)
DHS	0.3–0.4	–0.423	0.183	3.575	3.544	0.000	0.001
	0.4–0.5	–0.425	0.201	3.287	3.288	0.001	0.001
	0.5–0.6	–0.473	0.186	6.081	5.883	0.000	0.000
	0.6–0.7	–0.396	0.221	2.392	2.450	0.018	0.015
	0.7–0.8	–0.323	0.196	–	–	–	–
	>0.8	–0.200	0.076	–0.881	–2.132	0.381 (NS)	0.224 (NS)
XSBN	0.3–0.4	–0.398	0.322	0.323	0.331	0.747 (NS)	0.745 (NS)
	0.4–0.5	–0.424	0.307	0.665	0.652	0.507 (NS)	0.524 (NS)
	0.5–0.6	–0.410	0.329	0.456	0.475	0.649 (NS)	0.641 (NS)
	0.6–0.7	–0.412	0.272	0.563	0.499	0.574 (NS)	0.625 (NS)
	0.7–0.8	–0.370	0.313	–	–	–	–
	>0.8	–0.036	0.092	3.632	3.503	0.000	0.001
NMG	0.3–0.4	–0.033	0.107	3.068	3.256	0.002	0.002
	0.4–0.5	–0.011	0.102	2.023	2.098	0.044	0.041
	0.5–0.6	–0.016	0.118	2.059	2.412	0.040	0.020
	0.6–0.7	0.034	0.112	–0.452	–0.508	0.651 (NS)	0.641 (NS)
	0.7–0.8	0.025	0.098	–	–	–	–
	>0.8	–0.462	0.109	2.582	2.449	0.010	0.016
HB	0.3–0.4	–0.494	0.104	4.694	4.469	0.000	0.000
	0.4–0.5	–0.500	0.126	5.249	4.965	0.000	0.000
	0.5–0.6	–0.510	0.122	6.252	6.075	0.000	0.000
	0.6–0.7	–0.449	0.089	2.402	2.386	0.017	0.018
	0.7–0.8	–0.427	0.091	–	–	–	–
	>0.9	–0.481	0.162	1.011	0.581	0.314 (NS)	0.619 (NS)



**Fig. 5.** Relationship (a) and exponential regression (b) between LUE and the clearness index ( $k_t$ ) for highest interval of solar elevation angles at CBS, DHS, XSBN, and HB during the mid-growing season in 2005 and at NMG during the mid-growing seasons in 2004 and 2005.

### 3.5. Change in WUE with the clearness index

The change in WUE with  $k_t$  in the five ecosystems during the mid-growing season is shown in Fig. 6. The relation between WUE and  $k_t$  was conic at CBS, DHS, and HB (Fig. 6a, b, and f). The regres-

**Table 5**

Regression coefficients of the exponential equation ( $\text{LUE}^a = ae^{bkt}$ ) at CBS, DHS, XSBN, and HB during the mid-growing season in 2005 and at NMG during the mid-growing seasons in 2004 and 2005.

Site	$a$	$b$	$R^2$
CBS (2005)	56.68	–1.74	0.58
DHS (2005)	42.92	–2.37	0.54
XSBN (2005)	52.15	–2.53	0.54
NMG (2004)	18.96	–3.45	0.50
NMG (2005)	14.49	–6.13	0.66
HB (2005)	37.85	–1.56	0.71

<sup>a</sup> Unit of LUE is  $\text{mmolCO}_2 \text{ mol}^{-1} \text{ quantum}$ .

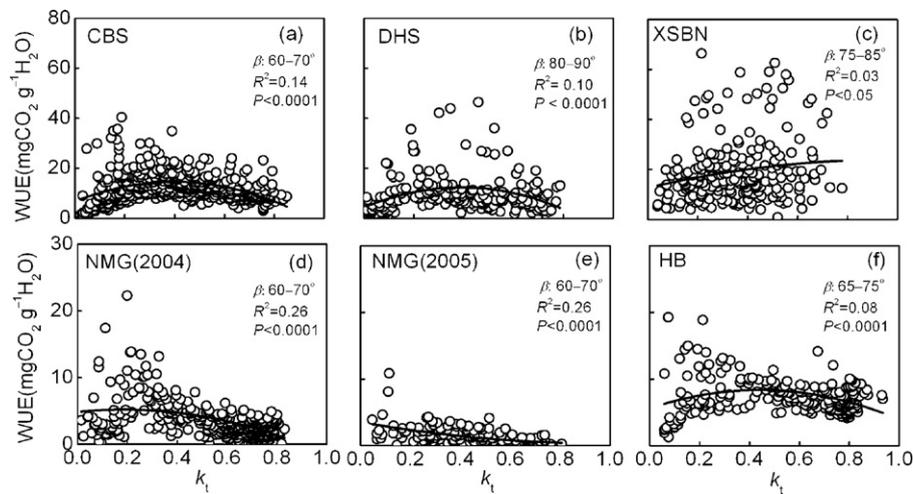
sion coefficients for the conic equations are provided in Table 6. The WUE reached a maximum when the value of  $k_t$  was about 0.4. When the value of  $k_t$  was larger than 0.4, WUE decreased (Fig. 6a, b, and f). These results indicate that partly cloudy sky conditions enhanced WUE of the three ecosystems. The changes in WUE with

**Table 6**

Regression coefficients of the conic equation ( $\text{WUE}^a = a k_t^2 + b k_t + c$ ) at CBS, DHS, XSBN, and HB during the mid-growing season in 2005 and at NMG during the mid-growing seasons in 2004 and 2005.

Site	$a$	$b$	$c$	$R^2$
CBS (2005)	–48.82	38.99	6.76	0.14
DHS (2005)	–52.34	40.91	4.34	0.10
XSBN (2005)	–11.85	23.04	12.73	0.03
NMG (2004)	–9.04	3.77	5.04	0.26
NMG (2005)	1.72	–5.03	3.27	0.26
HB (2005)	–14.15	12.48	5.61	0.08

<sup>a</sup> Unit of WUE is  $\text{mgCO}_2 \text{ g}^{-1} \text{ H}_2\text{O}$ .



**Fig. 6.** Relationship between WUE and the clearness index ( $k_t$ ) for the highest interval of solar elevation angles at CBS (a), DHS (b), XSBN (c), and HB (f) during the mid-growing season in 2005 and at NMG (d–e) during the mid-growing seasons in 2004 and 2005.

$k_t$  at NMG differed between the wet year (2004) and the dry year (2005) (Fig. 6d, e). In the wet year, the WUE was largest when the value of  $k_t$  was between 0.2 and 0.4, beyond which the WUE decreased (Fig. 6d). In contrast, poor water conditions in the dry year led to a near linear decrease in WUE with increasing  $k_t$  (Fig. 6e). Cloudy sky conditions increased the WUE of the grassland ecosystem at NMG. For the tropical forest ecosystem at XSBN, its WUE did not change with  $k_t$  during the mid-growing season (Fig. 6f). The results implied that cloudiness had limited impact on the WUE of the tropical rainforest in the mid-growing season.

## 4. Discussion

### 4.1. Variation of the responses of NEE, LUE and WUE to cloudiness with ecosystems

NEE, LUE, and WUE of the temperate forest ecosystem at CBS and subtropical forest ecosystem at DHS were greater under partly cloudy sky conditions than under clear sky conditions from June to August. This result is consistent with previous studies, which show that NEE of forest ecosystems reached its maximum values under cloudy sky conditions (Gu et al., 1999; Letts et al., 2005; Alton et al., 2007; Urban et al., 2007). The studies by Alton et al. (2007) reported that the LUE (defined as GPP/PAR) of three forest canopies (a sparse, boreal needleleaf; a temperate broadleaf and a dense tropical, broadleaf stand) increased by 6–33% when sky radiance was dominated by diffuse (cloudy sky) rather than direct sunlight (clear sky). Choudbury (2001) observed an increase in LUE by 50–180% under cloudy skies relative to clear skies in a temperate woodland. Many studies also indicated that WUE (defined as NEE/ET) of temperate forest ecosystems is higher during cloudy than clear periods (Lamaud et al., 1997; Freedman et al., 2001). Rocha et al. (2004) found that the midday canopy WUE (defined as GPP/ET) of a temperate deciduous forest increased linearly with increasing cloudiness.

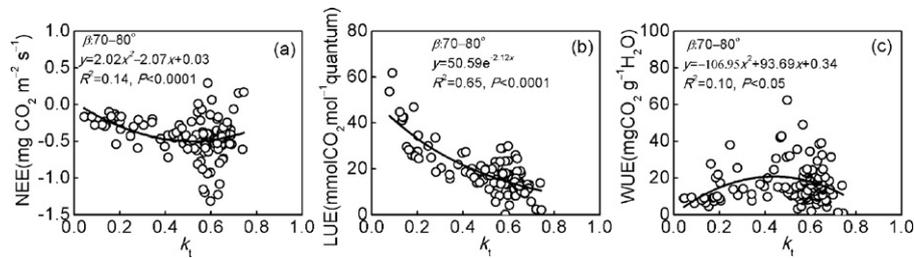
In this study, the LUE of the tropical rainforest ecosystem at XSBN increased under cloudy sky conditions compared to clear conditions from June to August. However, the NEE did not significantly increase under cloudy sky conditions compared to the clear sky conditions during the same period. This result is inconsistent with the study of Oliveira et al. (2007), where they reported that NEE of a forest ecosystem in Amazonia increased by less than 25% under cloudy skies. The difference of the two studies likely resulted from distinct water conditions during the observation periods. The study

of Oliveira et al. (2007) was performed in a dry season, whereas our observation was made in a wet season. To verify the result, we analyzed the changes in NEE, LUE, and WUE with cloudiness at XSBN in the dry seasons (from November to April). Like the study of Oliveira et al. (2007), the results showed that NEE at XSBN decreased when the value of  $k_t$  was larger than 0.6 in the dry seasons (Fig. 7a), and WUE decreased when the value of  $k_t$  was larger than 0.5 (Fig. 7c). Meanwhile, the LUE decreased exponentially with increasing cloudiness (Fig. 7b). These results indicate that the effect of cloudiness on carbon budget of tropical rainforest ecosystem in wet season differed from that in dry season. Under dry conditions, cloudy skies could increase NEE of tropical rainforest by improving ecosystem water conservation or reduce plant water demand.

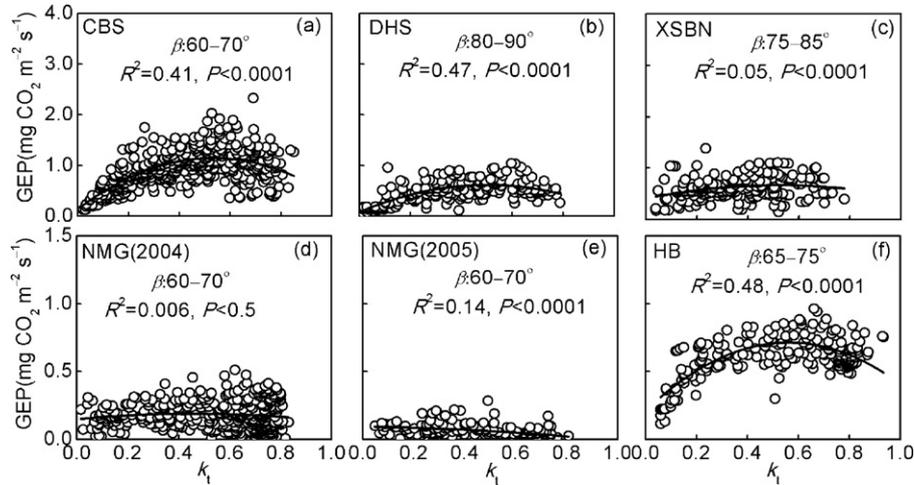
The NEE, LUE, and WUE of the two grassland ecosystems at NMG and HB increased under cloudy sky conditions. However, this is not in agreement with some previous studies (Niyogi et al., 2004; Letts et al., 2005), which reported that LUE and NEE of an ecosystem with low LAI, such as grassland and shrubs, did not increase on cloudy days. We attribute this inconsistency to the differences of climate conditions of the studied ecosystems, such as light, water, and thermal conditions.

### 4.2. Mechanisms controlling the responses of NEE, LUE and WUE to cloudiness in different ecosystems

NEE between terrestrial ecosystems and the atmosphere is the balance between gross ecosystem productivity (GEP) and ecosystem respiratory effluxes ( $R_e$ ) from autotrophic and heterotrophic sources. Therefore, the effects of cloudiness on NEE are determined by the responses of the two processes to the changes in cloudiness. At CBS, DHS, and HB sites, the relationship between GEP and clearness index ( $k_t$ ) for a given solar radiation angle was significantly conic (Fig. 8a, b, and f). The GEP reached its maximum under cloudy skies with  $k_t$  value being about 0.5 at the three sites. At XSBN, the GEP reached saturation when the  $k_t$  value was larger than 0.5 and did not decrease significantly under clear skies (Fig. 8c). The change in GEP with cloudiness was little at NMG (Fig. 8d and e). Except at DHS and NMG sites, the  $R_e$  at CBS, XSBN, and HB sites did not change significantly with  $k_t$  (Fig. 9). The responses of GEP and  $R_e$  to cloudiness at the five sites indicate that the changes in GEP with cloudiness determined the cloudiness effect on NEE at CBS, DHS, XSBN, and HB. However, the change in  $R_e$  due to cloudiness contributed most to the effect of cloudiness on NEE at NMG. The responses of GEP and  $R_e$  to the changes in cloudiness could



**Fig. 7.** Relationship between NEE (a), LUE (b), WUE (c) and the clearness index ( $k_t$ ) for the highest interval of solar elevation angles at XSBN during dry season (from November 2005 to April 2006).



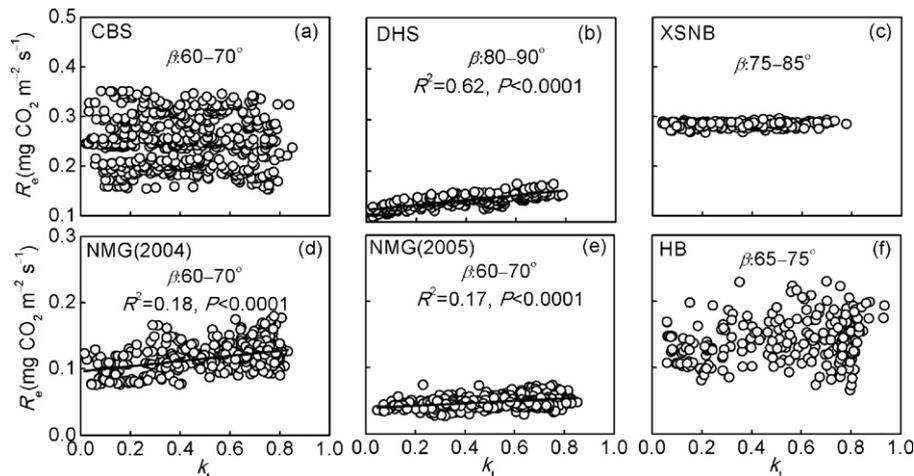
**Fig. 8.** Relationship between GEP and the clearness index ( $k_t$ ) for the highest interval of solar elevation angles at CBS (a), DHS (b), XSBN (c), and HB (f) during the mid-growing season in 2005 and at NMG (d-e) during the mid-growing seasons in 2004 and 2005.

be subject to cloudiness-induced changes in other environmental conditions.

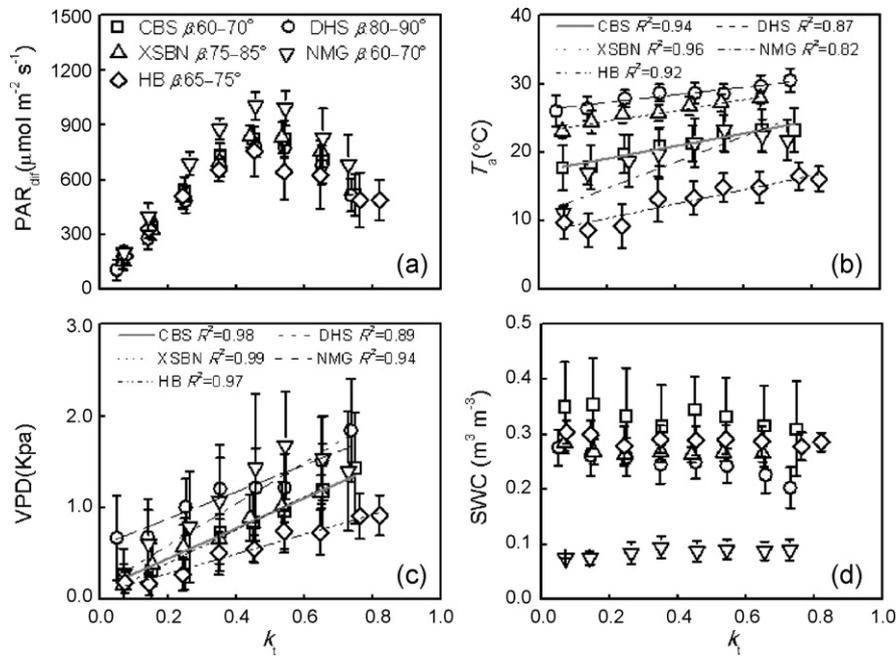
For a given solar radiation angle, global radiation received by ecosystem and balance of diffuse and direct components of solar radiation received by ecosystem change with cloudiness. Other environmental factors (e.g.,  $T_a$ , VPD) that control carbon exchange process between the atmosphere and ecosystem also change correspondingly (Gu et al., 1999). At the five sites of this study, the diffuse PAR received by ecosystem reached maximum under cloudy skies with  $k_t$  value about 0.5 (Fig. 10a). Moreover,  $T_a$  and VPD at the five sites increased linearly with the decrease in cloudiness (Fig. 10b and

c). However, SWC did not change significantly when sky became clear. These phenomena indicate that the carbon budget of the five ecosystems could be affected by diffuse PAR received by ecosystem,  $T_a$ , and VPD.

Under clear sky conditions, the sunlit leaves of canopy are often light saturated causing low LUE, whereas shaded leaves of canopy with high LUE suffered from a lower exposure to incoming radiation. Under cloudy sky conditions, although total solar radiation and direct radiation received by the canopy decreases, the portion of diffuse radiation increases, producing a more uniform irradiance of the canopy with a smaller fraction of the canopy likely to be light



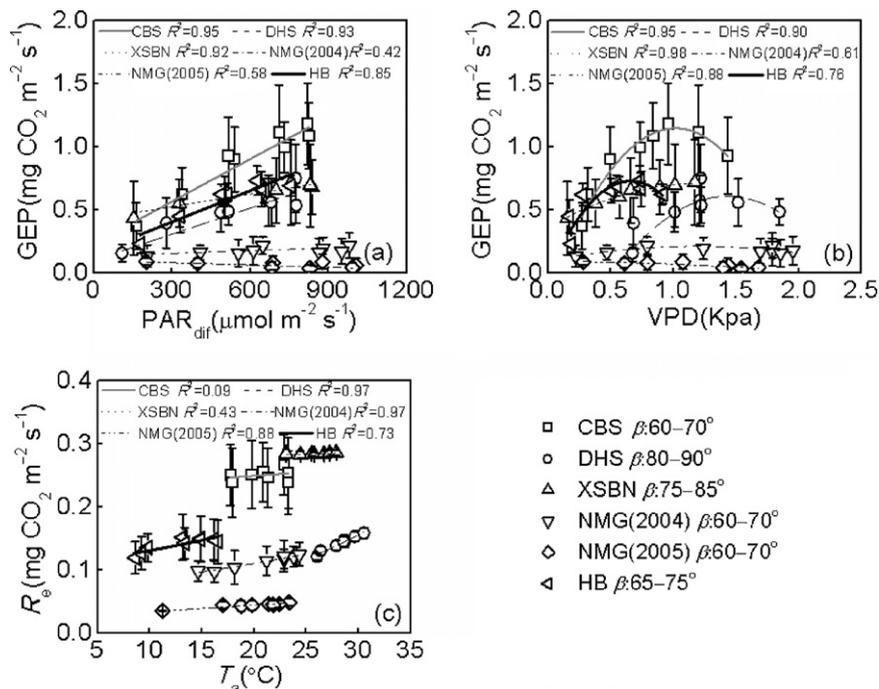
**Fig. 9.** Relationship between  $R_e$  and the clearness index ( $k_t$ ) for the highest interval of solar elevation angles at CBS (a), DHS (b), XSBN (c), and HB (f) during the mid-growing season in 2005 and at NMG (d-e) during the mid-growing seasons in 2004 and 2005.



**Fig. 10.** Relationship between diffuse PAR received by ecosystem ( $\text{PAR}_{\text{diff}}$ ) (a), air temperature ( $T_a$ ) (b), vapor press deficit (VPD) (c), soil water content (SWC) (d) and the clearness index ( $k_t$ ) for the highest interval of solar elevation angles at the five sites during the mid-growing season in 2005.  $\text{PAR}_{\text{diff}}$ , air temperature, vapor press deficit, and soil water content are the average for each  $k_t$  interval of 0.1.

saturated (Mercado et al., 2009). Therefore, LUE and photosynthesis of a canopy were enhanced under cloudy skies in comparison with clear skies (Gu et al., 2002; Farquhar and Roderick, 2003; Alton et al., 2007; Mercado et al., 2009). In this study, except semi-arid steppe at NMG, GEP of the forest ecosystems at CBS, DHS, and XSBN and alpine shrub at HB increased linearly with diffuse PAR received by ecosystem (Fig. 11a). Therefore, as skies became cloudy, increasing diffuse radiation received by ecosystem resulted in an increase in photosynthesis and LUE of the three forest ecosystems at CBS, DHS,

and XSBN and alpine shrub at HB. The difference in responses of GEP to diffuse PAR received by ecosystem between forest ecosystem and grassland ecosystem likely resulted from the difference in canopy structure. The LAI of forest ecosystem at CBS, DHS, and XSBN and alpine shrub at HB was higher than that of the semi-arid steppe at NMG (Table 1). The penetration of solar radiation through the canopy of the semi-arid steppe at NMG could be greater than in forest ecosystems. Therefore, increase in diffuse radiation under cloudy sky conditions might have very limited impact on GEP



**Fig. 11.** Relationship between diffuse PAR received by ecosystem ( $\text{PAR}_{\text{diff}}$ ) and GEP (a), vapor press deficit (VPD) and GEP (b), air temperature ( $T_a$ ) and  $R_e$  (c) for the highest interval of solar elevation angles at CBS, DHS, XSBN, and HB during the mid-growing season in 2005 and at NMG during the mid-growing seasons in 2004 and 2005.  $\text{PAR}_{\text{diff}}$ , VPD,  $T_a$ ,  $R_e$ , and GEP are the average for each  $k_t$  interval of 0.1.

(Fig. 11a) and LUE (Fig. 5) of the semi-arid steppe at NMG, compared to other four ecosystems.

Under sunny conditions, higher VPD may decrease stomatal conductance to CO<sub>2</sub> diffusion resulting in decrease in photosynthesis due to reduction of CO<sub>2</sub> concentrations at both chloroplasts and intercellular levels (Pantek and Goldstein, 2001; Raveh et al., 2003; Urban et al., 2007). On the contrary, decrease in VPD under cloudy skies induces stomatal openness thus enhancing canopy photosynthesis. For the ecosystems at CBS, DHS, and HB, the relationship between VPD and GEP was conic (Fig. 11b). Higher VPD under clear skies relative to cloudy skies decreased GEP of the three ecosystems (Fig. 11b). For the tropical rainforest at XSBN, GEP increased with VPD, but higher VPD under clear skies did not cause GEP decrease (Fig. 11b). Because of lower VPD and lowest solar radiation received by the tropical rainforest at XSBN from June to August (Fig. 2k and m) among the five ecosystems, the tropical ecosystem was obviously limited by light condition rather than water condition. Therefore, the increase in VPD under clear skies did not restrain the photosynthesis in this tropical rainforest. For the semi-arid steppe at NMG, VPD was highest in five ecosystems from June to August (Fig. 2r). The highest VPD and drier environmental conditions could restrain the ecosystem photosynthesis. As a result, when VPD increased under clear skies, the decrease in photosynthesis of this ecosystem was more significant in the drought year of 2005 than in the wet year of 2004 (Fig. 11b). Moreover, since higher VPD can increase the ET of canopy under clear sky conditions (Law et al., 2002; Monson et al., 2002), the decrease in GEP and increase in ET under clear skies can decrease WUE at CBS, DHS, NMG, and HB.

Temperature is a main environmental factor that influences ecosystem respiration when water condition is not a limiting factor (Lloyd and Taylor, 1994; Law et al., 2002; Yu et al., 2008b). Under cloudy sky conditions, air temperature and leaf temperature decrease, which cause a decrease in ecosystem respiration (Gu et al., 1999; Urban et al., 2007). Except for the NMG site, temperature is a primary factor that influences ecosystem respiration at all sites because the soil water content of these ecosystems were high from June to August (Fig. 2d and i). Compared to clear skies, the decrease in temperature under cloudy skies lowered the respiration of the ecosystems at DHS, XSBN, and HB (Fig. 11c). From June to August, NMG was the driest site among the five sites because of least precipitation (Fig. 2t) and lowest soil water content (Fig. 2s). This unfavorable moisture condition induced significant increase in ecosystem respiration at the site when temperature increased under clear skies (Fig. 11c). Moreover, evapotranspiration (ET) is also subject to temperature (Baldocchi, 1997; Yu et al., 2008a). Therefore, lower temperature under cloudy skies decreased the ET of the ecosystems at CBS, DHS, NMG, and HB.

Overall, the increase in GEP of the ecosystems at CBS, DHS, and HB with increasing ecosystem-received diffuse radiation under cloudy skies was the main factor causing increases in LUE and NEE compared to clear skies. Moreover, under cloudy skies, decreasing VPD caused the increase in GEP and the decrease in ET, while decreasing  $T_a$  led to the decrease in  $R_e$  and ET of the three ecosystems. These processes were partly responsible for the increases in NEE and WUE at CBS, DHS, and HB. For tropical rainforest ecosystem at XSBN, the increase diffuse radiation received by ecosystems under cloudy skies enhanced GEP and LUE. Under cloudy skies, the decrease in  $R_e$  with decreasing temperature was the main reason leading to the increase in net carbon uptake of the semi-arid steppe at NMG, compared to clear skies. Moreover, the increase in GEP with decreasing VPD under cloudy skies promoted LUE and WUE of this ecosystem. These results indicate that canopy characteristics and water conditions determine the differences in responses of carbon exchange processes of different ecosystems to cloudiness changes.

Solar radiation received by the ecosystems in alpine shrub at HB was stronger (Fig. 2u) among the five sites during the

mid-growing seasons. When sky becomes clear, the strong solar radiation received by ecosystem can exceed what is needed for carbon assimilation resulting in photo-inhibition (Öquist et al., 1992). Moreover, HB site has the highest altitude among the five sites and can suffer ultraviolet radiation (UV). Some studies have indicated that strong UV, especially ultraviolet-B (UV-B) radiation, can depress photosynthesis (Ekelund, 2000; Correia et al., 2005; Sangtarash et al., 2009; Li et al., 2010). Plants living in strong UV can regulate pigmentation and different enzyme mechanisms to reduce photosynthesis in order to protect themselves against high UV radiation (Franklin and Forster, 1997; Ekelund, 2000). Therefore, under clear skies, photosynthesis of the alpine shrub at HB may decrease to avoid stronger global solar radiation and the damage of UV-B. This may be one of the mechanisms that cause decrease in net carbon uptake of the alpine shrub ecosystem under clear skies.

Increase in aerosols also impacts the CO<sub>2</sub> exchange between land and atmosphere (Niyogi et al., 2004; Min, 2005; Oliveira et al., 2007). In China, the mean aerosol optical depth (AOD) at HB, CBS, and XSBN were 0.09, 0.19, and 0.42, respectively (Wang et al., 2006). The mean AOD of Guangzhou city, where DHS site is nearby, was 0.44 (Zong et al., 2005), indicating a higher AOD at DHS site than other study sites. These data imply that the potential influence of aerosol on ecosystem carbon budget processes might be larger at XSBN and DHS than at HB and CBS. In the future, we will further explore the effects of aerosol on net carbon uptake in these ecosystems through collecting the aerosol data.

#### 4.3. Potential impact of cloudiness patterns on net carbon uptake

Under cloudy condition with  $k_t$  about 0.5, the NEE of the temperate (e.g. CBS, NMG and HB) and subtropical (e.g. DHS) ecosystems reached maximum (Fig. 4) (Table 4). Unfortunately, the peaks of the  $k_t$  frequency distribution at the five sites were not consistent within the  $k_t$  about 0.5 (Fig. 3). This suggests that the pattern of cloudiness from 2003 to 2006 was not the best for net carbon uptake in the north temperate ecosystem and south subtropical and tropical ecosystems of China. Annual precipitation has decreased in North and Northeast China and in the middle and lower Yangtze River basin since the 1990s (Wang et al., 2004; Ding et al., 2006). This changes in precipitation implied that clear days would increase in the North and Northeast of China but decrease in South China. Based on our results, the changing trend of sky conditions in China did not encourage a potential increase in the net carbon uptake for north temperate ecosystem and south subtropical and tropical ecosystem. Moreover, based on prediction of Hadley Centre Global Environmental Model (version HadGEM2-A) under IPCC SRES A1B scenario modified to stabilize at 450 ppmv CO<sub>2</sub> equivalent, the diffuse PAR will decrease during the twenty-first century because of decreasing anthropogenic aerosols emissions (Mercado et al., 2009). These changes in sky conditions and diffuse radiation will increase the uncertainty in evaluation of net carbon uptake of terrestrial ecosystems in the future.

Understanding the responses of NEE, LUE and WUE of different ecosystems of China to change in cloudiness can improve prediction of net carbon absorption and water cycle in the Asia monsoon region under climate change. Identification of the changing tendency of cloudiness in different regions would be useful for ecosystem carbon sink/source management, such as water conservation above threshold level and establishment of ideal canopy architecture through plant replacement. The influence of cloudiness on ecosystem carbon and water exchange processes also depends upon local thermal, moisture, and light conditions of ecosystems as well as their interactions. To more accurately quantify the response of NEE, LUE and WUE to cloudiness in Asia monsoon region, we need the information of the change tendency of cloudiness in different regions. For mechanistic understand-

ing, further studies should be performed based on process-models to clarify how the changes in ecosystem-received diffuse radiation and other environmental factors due to cloudiness affect carbon exchanges processes in different types of ecosystems. In addition, the data of aerosol should be collected to distinguish the effects of aerosol and cloudiness, especially for sub-tropical forest and/or tropical rainforest ecosystems. The influence of UV on photosynthesis at high altitude area is also an issue to be clarified.

## 5. Conclusions

We assessed the responses of NEE, LUE, and WUE to cloudiness in five typical ecosystems of China. We found that:

- (1) Cloudy sky conditions with a  $k_t$  value between 0.4 and 0.6 can enhance the NEE, LUE, and WUE of temperate ecosystems (e.g., CBS, NMG, and HB) and subtropical forest ecosystem (e.g., DHS) in China from June to August. For the tropical rainforest ecosystem at XSBN, the LUE was larger under cloudy sky conditions than under clear sky conditions, but the NEE and WUE did not significantly change.
- (2) The increase in GEP with increasing ecosystem diffuse radiation under cloudy skies was the main reason for the increase in net carbon uptake of the forest ecosystems at CBS and DHS and the alpine shrub ecosystem at HB. The decrease in  $R_e$  with decreasing temperature under cloudy skies was mainly responsible for the increase in net carbon uptake of the semi-arid steppe at NMG.
- (3) The increase in GEP and decrease in ET with increasing ecosystem diffuse radiation and decreasing in VPD under cloudy skies resulted in increasing LUE and WUE of the forest ecosystems at CBS, DHS, alpine shrub ecosystem at HB, and semi-arid steppe at NMG. The differences in changes in carbon exchange processes with cloudiness in different ecosystems depend on canopy characteristics and water conditions.
- (4) Although partly cloudy sky benefits enhancing net carbon uptake of temperate ecosystems (e.g., CBS, NMG, and HB) and subtropical forest ecosystem (e.g., DHS), the pattern of cloudiness in the five sites during mid-growing seasons from 2003 to 2006 was unfavorable for increasing net carbon uptake of these ecosystems.

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