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ORIGINAL ARTICLE

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Comparing the impact of cloudiness on carbon dioxide exchange in a grassland and a maize cropland in northwestern China

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Abstract Light quantity and quality strongly influence plant growth. However, different ecosystems have different capabilities to assimilate solar radiation. In this study, the effects of cloudiness intensity on the net ecosystem exchange of carbon dioxide (NEE) were compared between an alpine grassland (with lower leaf area index) at A'Rou and an oasis maize cropland (with higher leaf area index) at Yingke, using flux data obtained during the middle of the growing season (July–August) in 2008 and 2009. The results showed that the response of NEE to photosynthetically active radiation (PAR) was more negative (carbon uptake) under cloudy than under clear skies at both sites. The maximum NEE occurred when the clearness index (CI) ranged from 0.4 to 0.7 under cloudy skies. The maximum enhancements were 11.9% for solar elevation angles of 60–65° in the grassland, and 34.9% for solar elevation angles of 60–65° and 10.3% for angles of 35–40° in the maize cropland before the irrigation period. The response of NEE to CI changed slightly with solar elevation angle in the grassland compared to the maize cropland. The results indicate that enhanced NEE under cloudy skies can be attributed to increasingly diffuse PAR and interactions with environmental factors (air temperature and vapor pressure deficit).

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Introduction

Light is essential to plant growth. The quantity, quality and duration of light greatly impacts the health and growth of all plants. Clouds, as a natural weather element, strongly influence environmental conditions on the surface of the ground (Bar-Or et al. 2010; Gu et al. 1999). Clouds alter the proportion of diffuse radiation among the solar radiation that reaches the Earth's surface. Diffuse and direct beam radiation differ in the way they pass through plant canopies, differentially affecting the summation of nonlinear processes such as photosynthesis in field settings.

The solar radiation received by ecosystems is the primary driver influencing daytime carbon uptake during the growing season (Guan et al. 2006). However, the solar radiation received by an ecosystem during heavy cloud cover is insufficient for canopy photosynthesis (Alton 2008). Thus, the net effect on photosynthesis of variations in radiation levels associated with an increases in cloud cover or scattered aerosols depends on the balance between the reduction in total photosynthetically active radiation (PAR) (which tends to reduce photosynthesis) and the increase in the diffuse fraction of the PAR (which tends to increase photosynthesis) (Mercado et al. 2009). However, the relationship between clouds and ecosystem CO_2 exchange can be more complicated, as changes in cloudiness alter other environmental factors that could influence the ecosystem carbon cycle (Gu et al. 1999; Zhang et al. 2010). For example, changes in vapor pressure deficit (VPD), air temperature (T_a), and soil temperature can significantly affect carbon exchange (Aires et al. 2008; Zhang et al. 2010; Zhao et al. 2006).

The influence of cloudiness on the NEE has primarily been studied in forests; other ecosystem types have received much less attention. For systems with smaller leaf area indices (LAIs) and weaker photosynthetic capacities (e.g., grasslands and shrublands), the positive effect of diffuse radiation may be close to zero (Letts et al. 2005; Niyogi et al. 2004), although more light penetrates through the canopy. In maize croplands with high LAI, light penetration may be reduced due to high plant density. Key issues to be resolved, however, include how changes in cloud cover will affect the ability of plants to photosynthesize, and how changes in photosynthesis will in turn amplify or suppress net carbon exchange in ecosystems.

The grasslands of the Qinghai–Tibetan Plateau (QTP) form a globally significant biome. Due to its unique geographic and ecological conditions, the grassland ecosystem has been reported to play an important role in the regional and national carbon cycle (Kato et al. 2004). In addition, the QTP is a region that is very sensitive to climate change. The Zhangye Region, one of the oases in the Gansu Province of China, is an important commodity grain production base and is famous for its high crop production in arid and semi-arid areas of northwestern China (Luo et al. 2005). Therefore, a discussion of the carbon cycle in these two types of ecosystems under cloudy conditions will provide not only a clearer understanding of carbon cycle processes, but also important data for evaluating carbon stability in the Northern Hemisphere's terrestrial ecosystem.

Thus, the objective of this study was to compare the effects of cloudiness on the NEE under clear and cloudy skies, and then to analyze and compare the impact of cloud cover on NEE in two ecosystems (grassland and maize cropland) with clearly different canopy structures and climate conditions.

Materials and methods

Site information

The study regions—the A'Rou (AR) grassland (100°27′E, 38°03′N, 3033 m a.s.l.) and the Yingke (YK) maize cropland (100°25′E, 38°51′N, 1520 m a.s.l.)—are, respectively, situated in the upper and middle regions of the Heihe River Basin, which is the second largest inland river basin in northwestern China. The mean annual temperatures of AR and YK are 0.7 and 6.5°C, and their average annual precipitations are 400 and 125 mm, respectively. AR is a typical short alpine grassland in the QTP. YK is a typical irrigated farmland situated in the Zhangye oasis, for which the primary crops are maize and wheat. An eddy covariance (EC) flux sensor was mounted in the maize cropland. The alpine grassland was dominated by *Kobresia* species. During the study period, large parts of the grassland area were also covered by noxious weeds such as *Stellera chamaeiasme* and *Oxytropisis*. The soil type in the grassland is clay loam on the surface and sandy clay loam in deeper layers. The soil type in the maize cropland (*Zea mays* L.) is silt clay loam on the surface and silt loam in the deeper layers. Table 1 provides extensive descriptions of the two sites.

Field measurements

The EC flux sensors were mounted at heights of 2.81 and 3.15 m above the ground at AR and YK, respectively. The equipment in the EC tower included an open-path infrared gas analyzer (LI-7500, Li-Cor, Inc., Lincoln, NE, USA) and a three-dimensional ultrasonic anemometer (CSAT-3, Campbell Scientific Inc., Logan, UT, USA). Wind speed, sonic virtual temperature, CO_2 concentrations, and H_2O concentrations were sampled at 10 Hz, and the data were stored in a data logger (CR5000, Campbell Scientific Inc.).

All meteorological data were recorded using an automated weather station along with the flux measurements. Standard meteorological and soil parameters were measured continuously with an array of sensors. Solar radiation was measured with a four-component net radiometer (PSP/PIR, Eppley, UAS) at different heights above the ground. Air humidity and air temperature profiles were measured using shielded and aspirated probes (HMP45C, Vaisala, Helsinki, Finland). Rainfall was measured with a tipping-bucket rain gauge (TE525, Campbell Scientific Inc.).

Table 1 Site information

Sites	A'Rou	Yingke
Location	100°27′E, 38°03′N	100°25′E, 38°51′N
Elevation (m)	3033	1520
Mean annual temperature (°C)	0.7	6.5
Annual precipitation (mm)	400	125
Canopy height (cm)	20–30	150–200
Maximum leaf area index (LAI)	1.3–2.0	3.5–5.2
Aboveground biomass (g m^{-2})	130–240	950–1350
Vegetation type	*Kobresia*, *Stellera chamaeiasme*, *Oxytropisis*	*Zea mays* L.
Water available	Precipitation	Irrigation, precipitation
Soil type	Clay loam	Silt clay loam
Soil organic matter (g/kg) at a depth of 0–35 cm	37.2–79.2	7.4–18.9
EC systems information	2.81 m (height) LI-7500	3.15 m (height) LI-7500

In this study, we only used the data measured during the middle of the growing season (July–August) in 2008 and 2009, as the canopy height and canopy density were almost constant during this period.

Flux data processing

The post-processing software Edire (University of Edinburgh, UK) was used to compute flux covariance from the raw data. Half-hourly fluxes of CO_2 (NEE) were determined by the eddy covariance method as the mean covariance between fluctuations in vertical wind speed and CO_2 concentration. The calculations included a 3-D coordinate rotation, spike detection, and checks for instantaneous records exceeding realistic absolute limits. In addition, air density fluctuations were used to correct the CO_2 fluxes (Webb et al. 1980). Storage below the EC height was calculated using the temporal change in CO_2 concentration above the canopy measured with the LI-7500. To fill in missing data due to sensor malfunctions, we adopted an approach that combined measurement, interpolation, and empirical data synthesis (Falge et al. 2001; Xu and Baldocchi 2004).

Data processing

Defining clearness index

The clearness index (CI) can be used as an indication of cloudiness, and has been widely used in previous solar radiation research (Okogbue et al. 2009; Tsubo and Walker 2005; Woyte et al. 2007). CI is defined as the ratio of the global solar radiation (S) received at the Earth's surface to the extraterrestrial irradiance (S_e) at a plane parallel to the Earth's surface (Gu et al. 1999), such that

$$CI = \frac{S}{S_e} \quad (1)$$

$$S_e = S_{sc}\,[1 + 0.033\cos(360\,t_d/365)]\sin\beta \quad (2)$$

$$\sin\beta = \sin\varphi\cdot\sin\delta + \cos\varphi\cos\delta\cos\omega \quad (3)$$

where S_{sc} is the solar constant (1367 W m^{-2}), t_d is the day of the year, β is the solar elevation angle, φ is the degree of latitude, δ is the declination of the sun, and ω is the time angle.

Defining clear skies

To quantify the influence of clouds on NEE, we set the clear-sky NEE as the baseline for comparison. Clear mornings and afternoons were identified based on two criteria. First, CI must increase smoothly with sin β. Second, the curve of the relationship between the clear-sky CI and sin β must form an envelope in the lumped scatter plot of CI against sin β.

Total PAR and diffuse PAR

To examine the potential factors controlling and contributing to the influence of clouds and aerosols on carbon uptake, we also studied the relationships between NEE and total PAR, diffuse PAR, VPD, and air temperature. Because of a lack of measurements of total PAR and diffuse PAR, total PAR was estimated from the solar radiation (Li et al. 2010) and diffuse PAR was calculated based on CI and β (Gu et al. 1999). The corresponding equations are as follows:

$$PAR_{dif} = PAR_{tot}\frac{[1+0.3\,(1-q^2)]\,q}{1+(1-q^2)\cos^2(90^\circ-\beta)\cos^3\beta} \quad (4)$$

$$PAR_{tot} = 0.45S \quad (5)$$

$$q = (S_f/S_e)/CI \quad (6)$$

interval: $0 \le CI \ge 0.3$; constraint: $S_f/S_e \le CI$

$$S_f/S_e = CI\,(1.020 - 0.254\,CI + 0.0123\sin\beta) \quad (7)$$

interval: $0.3 < CI > 0.78$; constraint: $0.1\,CI \le S_f/S_e \le 0.97\,CI$

$$S_f/S_e = CI\,(1.400 - 1.749\,CI + 0.177\sin\beta) \quad (8)$$

interval: $0.78 \le CI$; constraint: $0.1\,CI \le S_f/S_e$

$$S_f/S_e = CI\,(0.486\,CI - 0.182\sin\beta), \quad (9)$$

where PAR_{tot} is the total PAR, PAR_{dif} is the diffuse PAR, and S_f is the total diffuse radiation received by the horizontal plane at the Earth's surface (W m^{-2}).

Quantifying the influence of clouds on NEE

To quantify the magnitude of the influence of clouds on the NEE measurements relative to clear-sky NEE measurements (%NEE), the following expression was used:

$$\%NEE = \frac{100\,[NEE(\alpha) - NEE_{clear-sky}(\alpha)]}{NEE_{clear-sky}(\alpha)}. \quad (10)$$

NEE(α) is the measured NEE in the given sky conditions for the solar zenith angle α, and $NEE_{clear-sky}$ (α) is the measured NEE on clear-sky days.

Results

Environmental conditions

The seasonal variations in the mean monthly air temperature, monthly cumulative global solar radiation, and monthly cumulative precipitation at the AR and YK sites during the study period are shown in Fig. 1. The seasonal variations in the environmental factors in the two ecosystems were not exactly the same. In the AR grassland, the weather was cold and wet during the growing season, whereas in the YK cropland, the

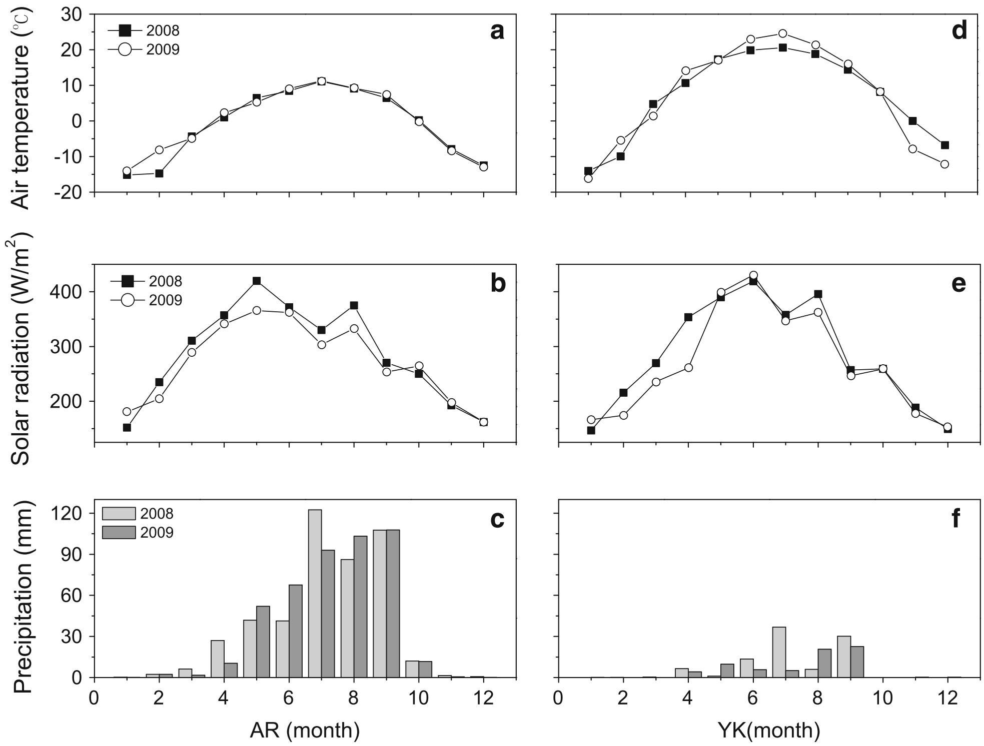

Fig. 1 Seasonal variations in air temperature (**a**, **d**), global solar radiation (**b**, **e**), and precipitation (**c**, **f**) in 2008 and 2009 at the A'Rou (AR) grassland (**a–c**) and the Yingke (YK) maize cropland (**d–f**)

weather was warm and dry. Maize in YK mainly depends on irrigation, while the AR grassland depends on precipitation.

Response of NEE to PAR under clear and cloudy skies

Because photosynthesis is driven by light, we first examined how NEE responds to PAR under cloudy and clear skies at both sites. The rectangular hyperbolic formulation has been widely used to describe the relationship between NEE and PAR; however, its one drawback is that it cannot account for a reduction in NEE at high light intensity (Letts et al. 2005). Therefore, we explored polynomial functions to describe the relationship between NEE and PAR. There was one irrigation event during the study period at the YK station. To eliminate the effect of quick soil moisture changes, the data from YK was divided into two parts (before and after irrigation). Changes in NEE with PAR under clear and cloudy skies are shown in Fig. 2 during the study period at both sites. A cubic regression curve fitted to the data described the relationship between NEE and PAR under clear and cloudy skies. NEE was more negative under cloudy than under clear skies at both sites during the study period. This result indicates that net carbon uptake was higher under cloudy skies.

Changes in NEE with clearness index

To further explore the effect of changes in cloudiness on NEE, we analyzed the response of NEE to changes in CI at the AR grassland and at the YK cropland. CI typically ranged from 0.05 to 0.85. We grouped the data into 5° intervals of solar elevation angle to eliminate the effect of solar elevation angle on the responses of NEE to CI. In this paper, we only present the results from 2009. NEE reached its maximum values when CI fell between 0.4 and 0.7 (Fig. 3) for the AR grassland and between 0.5 and 0.7 for the YK cropland. However, changes in NEE were more obvious with increased CI in the YK maize cropland (Fig. 3c–f) than in the AR grassland (Fig. 3a, b). NEE decreased when the value of CI exceeded 0.5 at AR. NEE decreased when the value of CI exceeded 0.7 and 0.6 before and after the irrigation period at YK, respectively. This result indicates that the grassland has a lower light saturation level than the maize cropland.

Magnitude of NEE enhancement by clouds

To minimize the influence of solar elevation angles on the relationship between CI and changes in NEE on cloudy days relative to days with clear skies (%NEE), the calculations were grouped into 5° intervals of solar elevation angle. We found a similar variation in %NEE

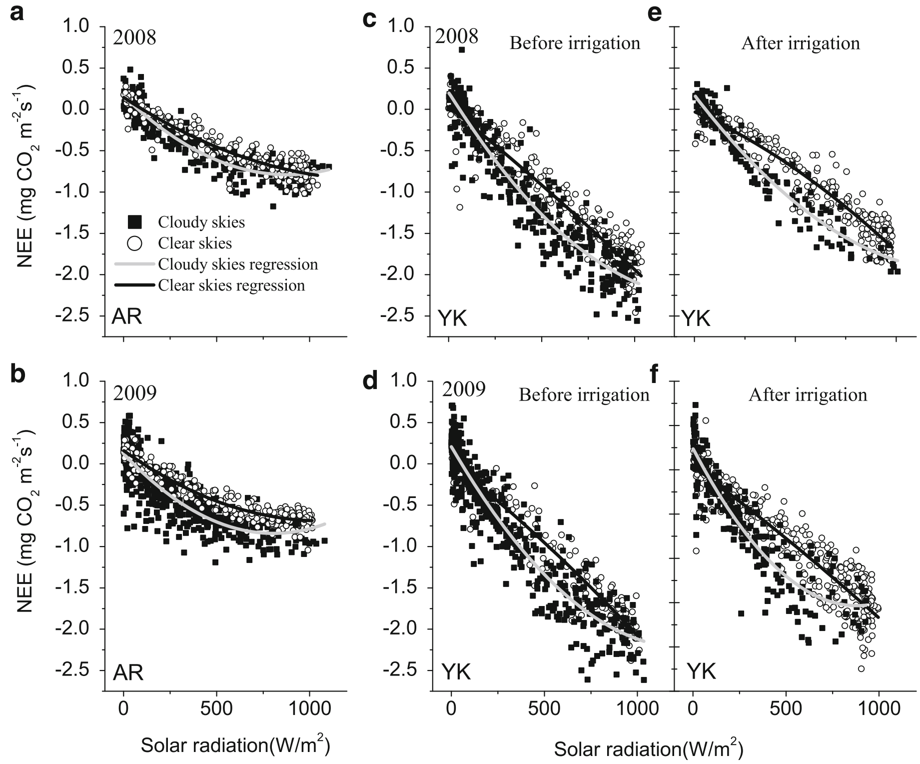

Fig. 2 The relation between net ecosystem exchange of CO_2 (NEE) and solar radiation under clear and cloudy skies from July to August in 2008 (**a**, **c**, **e**) and 2009 (**b**, **d**, **f**) at the A'Rou (AR) grassland (**a**, **b**) and the Yingke (YK) maize cropland (**c**–**f**)

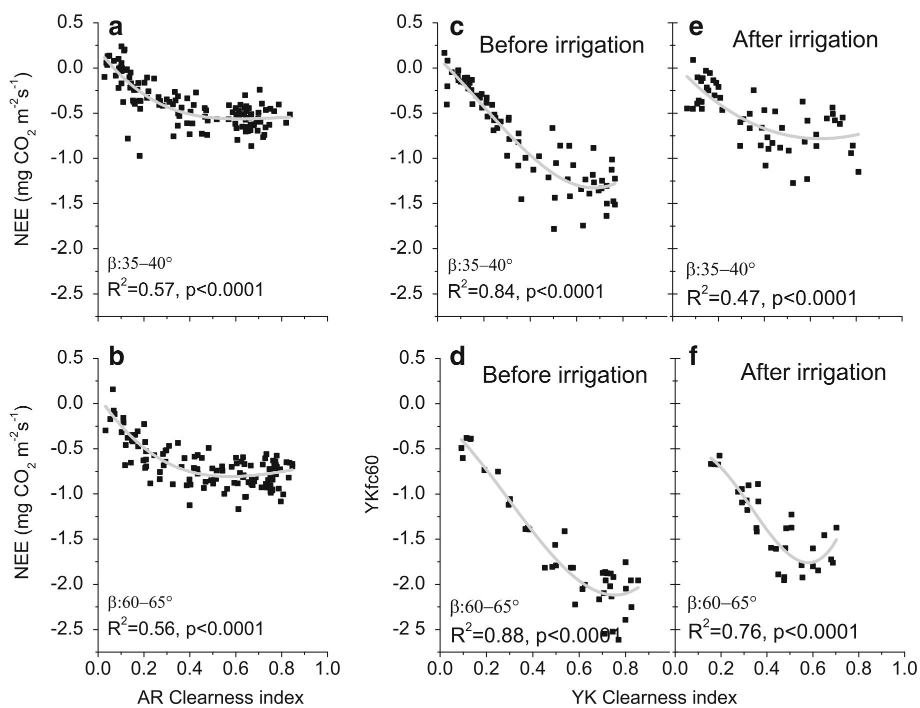

Fig. 3 The relationship between NEE and the clearness index (CI) for different intervals of solar elevation angle (**a**, **c**, **e**: 35–40°; **b**, **d**, **f**: 60–65°) from July to August in 2009 at the A'Rou (AR) grassland (**a**, **b**) and the Yingke (YK) maize cropland (**c**–**f**), respectively

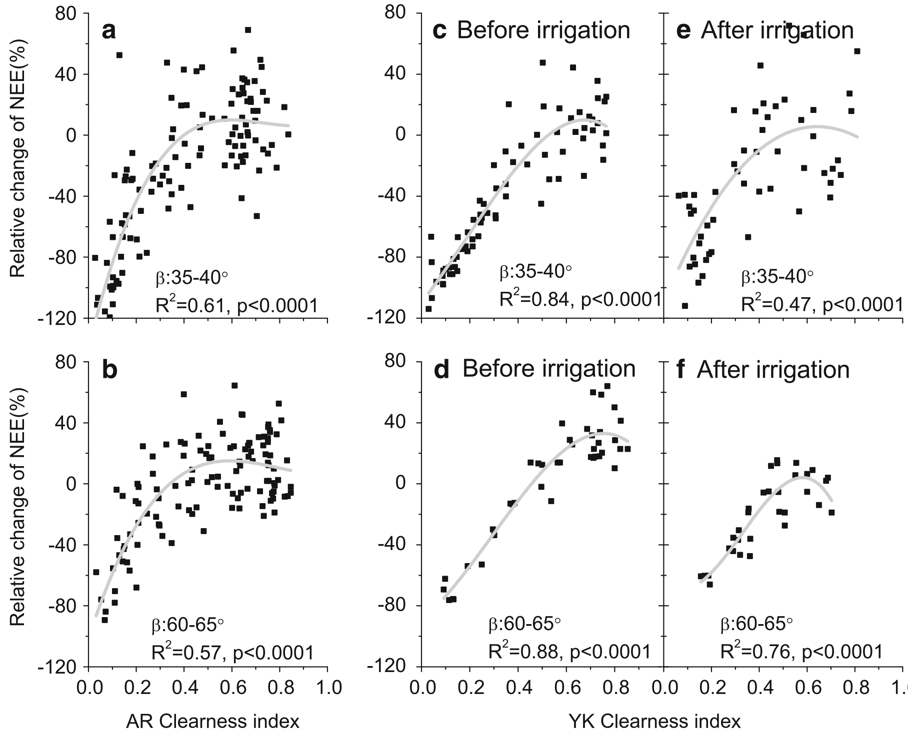

Fig. 4 The relationship between NEE enhancement under cloudy skies relative to clear skies and clearness index (CI) for different intervals of solar elevation angle (**a**, **c**, **e**: 35–40°; **b**, **d**, **f**: 60–65°) from July to August in 2009 at the A'Rou (AR) grassland (**a**, **b**) and the Yingke (YK) maize cropland (**c**–**f**), respectively

with CI in the two ecosystems. A cubic polynomial equation was fitted to describe the relationship between %NEE and CI (Fig. 4). The maximum %NEE at AR was 11.9% for solar elevation angles of 60–65°, and the maximum %NEEs were 34.9 and 10.3% for angles of 60–65° and 35–40° before the irrigation period at YK.

Discussion

The effects of changes in cloudiness on NEE

The NEE of the grassland ecosystem at AR and that of the maize cropland at YK reached their maxima under cloudy skies when the CI value was between 0.4 and 0.7. This finding is consistent with previous studies showing that the NEE of forest ecosystems reaches its maximum value under cloudy skies when the value of CI is between 0.4 and 0.7 (Gu et al. 1999; Jing et al. 2010; Zhang et al. 2010). However, relative to NEE at the AR grassland, the NEE of the maize cropland increased more when the value of CI was below 0.5 and decreased more when the value of CI exceeded 0.7. This result indicates that NEE at the maize cropland is more sensitive to strong solar radiation under cloudy skies. The previous studies (Yamasoe et al. 2006) noted that CO_2 flux from C4 vegetation is the most sensitive to aerosol cover, while C3 crops and grasslands are less sensitive and deciduous trees are moderately sensitive. Some peatland sites even showed a neutral response of NEE to increased cloud loading when the CI was higher than the light-saturated point (CI 0.37) (Letts et al. 2005). This finding indicates that the response of NEE as CI changes differs between ecosystems. The magnitude of the difference in NEE response to PAR between clear and cloudy days in different ecosystems largely depends on the quantity of diffuse PAR received by shaded leaves (Gu et al. 1999). Thus, the AR grassland, with its lower LAI, would not show any obvious differences in canopy photosynthesis between clear and cloudy days, in contrast to maize ecosystems, which have higher LAIs and carbon uptake capabilities.

We also examined the magnitude of the influence of clouds on the NEE measurements relative to clear-sky NEE measurements. The %NEE reached its maximum of 11.9% at a CI of 0.6 under cloudy skies in the AR grassland, and its maximum of 34.9% at a CI of 0.7 under cloudy skies in the YK maize cropland before irrigation (Fig. 4). However, except for the period at YK before irrigation with high solar elevation angles, all other enhancements under cloudy conditions were much lower than the values of more than 30% observed in a temperate forest (Gu et al. 1999) and 50% in a New Zealand beech forest (Hollinger et al. 1994). A possible explanation for this phenomenon is that the YK maize cropland, with its high leaf area index (LAI 3.5–5.2) and closed canopy, limited the transmittance of PAR deeper into the understory and inside the canopy (Johnson and Smith 2006; Yamasoe et al. 2006). For the grassland, with its low LAI and high transmittance, however, the

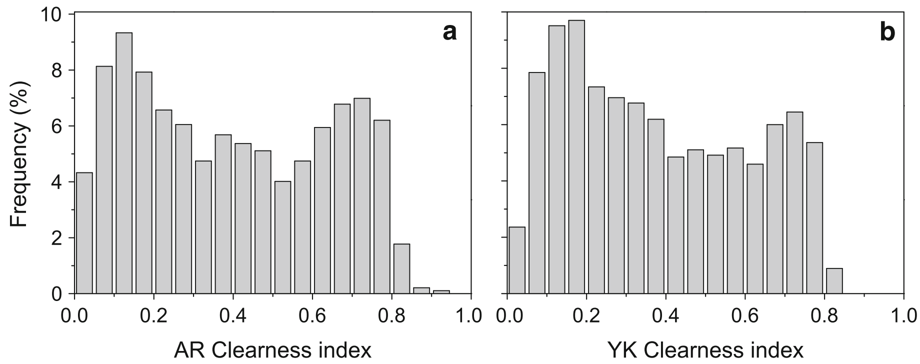

Fig. 5 The frequency distributions of the variation in the clearness index (CI) at the A'Rou (AR) grassland (**a**) and the Yingke (YK) maize cropland (**b**) during the study period

enhancement was suppressed by its low carbon uptake capability. Previous studies (Alton et al. 2007) found that when a sparse, boreal needle-leaf ecosystem, a temperate broadleaf ecosystem, and a dense tropical, broadleaf forest ecosystem were compared, the NEE of the boreal forest was the most sensitive to changes in shortwave radiation. Those findings suggest that high and sparse broadleaf ecosystems are beneficial to NEE enhancement.

NEE increased under cloudy sky conditions when the CI was between 0.4 and 0.7. However, for the entire range of CI (0–1), the magnitude of the reduction in NEE was greater than the amount by which it increased in both the grassland and the maize cropland. From Fig. 5, it is clear that most of the data are below 0.4 or between 0.7 and 0.8, indicating that the two ecosystems at our sites did not not have optically thick clouds.

The effects of changes in cloudiness on environmental factors

Light use efficiency was different under clear and cloudy skies, and altered environmental factors would also impact carbon exchange. Total solar radiation and diffuse solar radiation changed with clear and cloudy sky conditions. Correspondingly, other environmental factors (T_a, VPD, etc.) could also change. Those changes can influence carbon exchange between ecosystems and the atmosphere. Recent theoretical and observational studies (Alton 2008; Gu et al. 1999, 2002; Zhang et al. 2010) have demonstrated that canopy photosynthesis is more efficient under conditions with increased diffuse radiation. The relationships at both sites between the total PAR or the diffuse PAR and CI are shown in Fig. 6. Total PAR increased almost linearly as CI

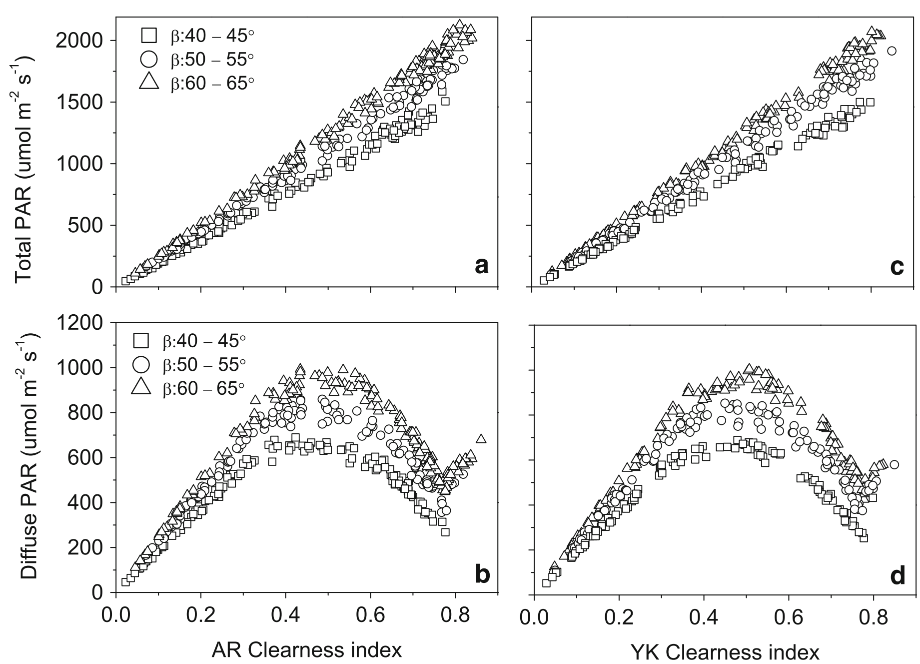

Fig. 6 Changes in total PAR (**a**, **c**) and diffuse PAR (**b**, **d**) with the clearness index (CI) for selected intervals of solar elevation angle at the A'Rou (AR) grassland (**a**, **b**) and the Yingke (YK) maize cropland (**c**, **d**) during the study period

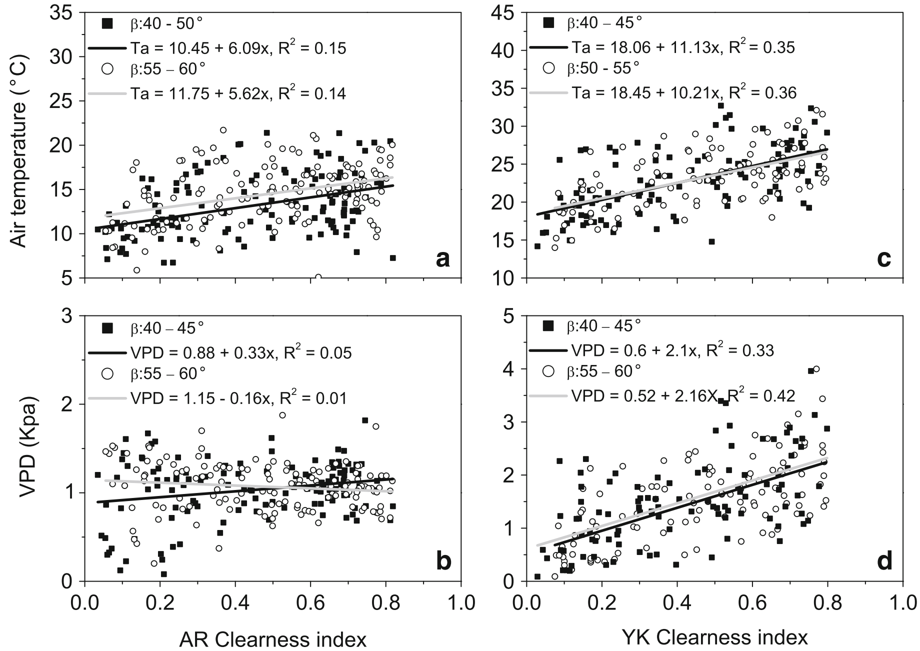

Fig. 7 Changes in air temperature (**a**, **c**) and vapor pressure deficit (VPD; **b**, **d**) with clearness index (CI) for selected intervals of solar elevation angle at the A'Rou (AR) grassland (**a**, **b**) and the Yingke (YK) maize cropland (**c**, **d**) during the study period

increased. However, the relationship between diffuse PAR and CI was not linear. Diffuse PAR generally increased with increasing CI until it reached the maximum value when CI was in the range 0.4–0.6, which was the range of diffuse PAR received by the ecosystem when it achieved its maximum NEE at both sites (Fig. 3a, b). This result indicates that carbon uptake of the grassland and maize ecosystems at AR and YK can increase as the diffuse PAR received by the ecosystem under cloudy skies increases.

VPD is an important factor that affects stomatal conductance, which regulates the exchange of carbon and energy between many plants, ecosystem processes, and the atmosphere (Bunce 2001; Damour et al. 2010). Generally, the photosynthetic rates of plants decrease with increasing VPD (Cunningham 2005). Therefore, the decrease in VPD associated with cloudy conditions can enhance canopy photosynthesis. Figure 7b–d shows how VPD changed under cloudy skies. VPD decreased linearly with decreasing CI under cloudy skies at YK, while there seemed to be no impact of CI on VPD in the AR grassland under cloudy skies. Our results suggest that the decreased VPD under cloudy skies can enhance photosynthesis in the YK maize cropland. The reason for this is partly that clouds can reduce the leaf temperature and increase the relative humidity, thus decreasing VPD and stimulating carbon uptake. Similar results have been found for forests (Min and Wang 2008). Canopy photosynthesis may not be enhanced by VPD under cloudy skies at the AR grassland.

Temperature also influences ecosystem respiration processes. Air temperature decreased linearly with decreasing CI at the AR grassland and the YK maize cropland (Fig. 7a–c). This decrease in T_a could cause a decrease in ecosystem respiration at the YK cropland. The AR grassland is located on the northeastern Tibetan Plateau, and a previous study found that temperature controls ecosystem CO_2 exchange in this area (Saito et al. 2009). Therefore, the decrease in T_a could cause a decrease in ecosystem respiration; however, ecosystem photosynthesis could also be depressed relative to cloudy sky conditions. The increased diffuse PAR and decreased VPD and T_a under cloudy skies could be beneficial to ecosystem photosynthesis and decrease ecosystem respiration of the YK maize cropland in the middle of the growing season. The carbon sink could be enhanced to a certain degree in the AR grassland by the increase in diffuse PAR and decrease in T_a under cloudy skies. Thus, cloudy sky conditions could increase net carbon uptake, based on the extent of optimum environmental conditions in the two ecosystems.

Conclusions

This work indicates that the net carbon exchange could improve in grassland and maize croplands under cloudy skies relative to clear skies. When CI was between 0.4 and 0.7, environmental factors were optimal for enhancing NEE in both ecosystems. CO_2 exchange in the grassland increased with CI until it reached the light saturation point (CI 0.4); it maintained a high level until the CI was near to 0.6, and then it begin to decrease. The maize cropland had a greater carbon uptake ability and a higher light saturation point (CI 0.7) before irrigation than after irrigation (CI 0.6), indicating that NEE in the maize cropland was more sensitive than that at the grassland. Under cloudy conditions, carbon exchange could be impacted by many environmental factors; for example, decreasing air temperature and VPD can promote canopy photosynthesis and decrease respiration. The results in our study showed that the increase in NEE under cloudy skies in the YK maize cropland was due to increased diffuse PAR and decreased VPD and T_a during the middle of the growing season. The enhanced NEE under cloudy skies at the AR grassland was mainly due to increased levels of diffuse PAR and decreased T_a.

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References

Aires LMI, Pio CA, Pereira JS (2008) Carbon dioxide exchange above a Mediterranean C3/C4 grassland during two climatologically contrasting years. Glob Change Biol 14:539–555

Alton PB (2008) Reduced carbon sequestration in terrestrial ecosystems under overcast skies compared to clear skies. Agric For Meteorol 148:1641–1653

Alton PB, North PR, Los SO (2007) The impact of diffuse sunlight on canopy light-use efficiency, gross photosynthetic product and net ecosystem exchange in three forest biomes. Glob Change Biol 13:776–787

Bar-Or RZ, Koren I, Altaratz O (2010) Estimating cloud field coverage using morphological analysis. Environ Res Lett 5:014022

Bunce JA (2001) Direct and acclimatory responses of stomatal conductance to elevated carbon dioxide in four herbaceous crop species in the field. Glob Change Biol 7:323–331

Cunningham SC (2005) Photosynthetic responses to vapour pressure deficit in temperate and tropical evergreen rainforest trees of Australia. Oecologia 142:521–528

Damour G, Simonneau T, Cochard H, Urban L (2010) An overview of models of stomatal conductance at the leaf level. Plant Cell Environ 33:1419–1438

Falge E, Baldocchi D, Olson R, Anthoni P, Aubinet M, Bernhofer C, Burba G, Ceulemans R, Clement R, Dolman H, Granier A, Gross P, Grunwald T, Hollinger D, Jensen NO, Katul G, Keronen P, Kowalski A, Lai CT, Law BE, Meyers T, Moncrieff H, Moors E, Munger JW, Pilegaard K, Rannik U, Rebmann C, Suyker A, Tenhunen J, Tu K, Verma S, Vesala T, Wilson K, Wofsy S (2001) Gap filling strategies for defensible annual sums of net ecosystem exchange. Agric For Meteorol 107:43–69

Gu LH, Fuentes JD, Shugart HH, Staebler RM, Black TA (1999) Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: results from two North American deciduous forests. J Geophys Res Atmos 104:31421–31434

Gu LH, Baldocchi D, Verma SB, Black TA, Vesala T, Falge EM, Dowty PR (2002) Advantages of diffuse radiation for terrestrial ecosystem productivity. J Geophys Res Atmos 107:4050

Guan DX, Wu JB, Zhao XS, Han SJ, Yu GR, Sun XM, Jin CJ (2006) CO_2 fluxes over an old, temperate mixed forest in northeastern China. Agric For Meteorol 137:138–149

Hollinger DY, Kelliher FM, Byers JN, Hunt JE, Mcseveny TM, Weir PL (1994) Carbon dioxide exchange between an undisturbed old growth temperate forest and the atmosphere. Ecology 75:134–150

Jing X, Huang J, Wang G, Higuchi K, Bi J, Sun Y, Yu H, Wang T (2010) The effects of clouds and aerosols on net ecosystem CO(2) exchange over semi-arid Loess Plateau of Northwest China. Atmos Chem Phys 10:8205–8218

Johnson DM, Smith WK (2006) Low clouds and cloud immersion enhance photosynthesis in understory species of a southern Appalachian spruce-fir forest (USA). Am J Bot 93:1625–1632

Kato T, Tang YH, Gu S, Cui XY, Hirota M, Du MY, Li YN, Zhao ZQ, Oikawa T (2004) Carbon dioxide exchange between the atmosphere and an alpine meadow ecosystem on the Qinghai–Tibetan Plateau, China. Agric For Meteorol 124:121–134

Letts MG, Lafleur PM, Roulet NT (2005) On the relationship between cloudiness and net ecosystem carbon dioxide exchange in a peatland ecosystem. Ecoscience 12:53–59

Li R, Zhao L, Ding YJ, Wang S, Ji GL, Xiao Y, Liu GY, Sun LC (2010) Monthly ratios of PAR to global solar radiation measured at northern Tibetan Plateau, China. Sol Energy 84:964–973

Luo F, Qi S, Xiao H (2005) Landscape change and sandy desertification in arid areas: a case study in the Zhangye Region of Gansu Province, China. Environ Geol 49:90–97

Mercado LM, Bellouin N, Sitch S, Boucher O, Huntingford C, Wild M, Cox PM (2009) Impact of changes in diffuse radiation on the global land carbon sink. Nature 458:1014–1087

Min QL, Wang SY (2008) Clouds modulate terrestrial carbon uptake in a midlatitude hardwood forest. Geophys Res Lett 35:L02406

Niyogi D, Chang HI, Saxena VK, Holt T, Alapaty K, Booker F, Chen F, Davis KJ, Holben B, Matsui T, Meyers T, Oechel WC, Pielke RA, Wells R, Wilson K, Xue YK (2004) Direct observations of the effects of aerosol loading on net ecosystem CO_2 exchanges over different landscapes. Geophys Res Lett 31:L20506

Okogbue EC, Adedokun JA, Holmgren B (2009) Hourly and daily clearness index and diffuse fraction at a tropical station, Ile-Ife, Nigeria. Int J Climatol 29:1035–1047

Saito M, Kato T, Tang Y (2009) Temperature controls ecosystem CO_2 exchange of an alpine meadow on the northeastern Tibetan Plateau. Glob Change Biol 15:221–228

Tsubo M, Walker S (2005) Relationships between photosynthetically active radiation and clearness index at Bloemfontein, South Africa. Theor Appl Climatol 80:17–25

Webb EK, Pearman GI, Leuning R (1980) Correction of flux measurements for density effects due to heat and water vapour transfer. Q J R Meteorol Soc 106:85–100

Woyte A, Belmans R, Nijs J (2007) Fluctuations in instantaneous clearness index: analysis and statistics. Sol Energy 81:195–206

Xu LK, Baldocchi DD (2004) Seasonal variation in carbon dioxide exchange over a Mediterranean annual grassland in California. Agric For Meteorol 123:79–96

Yamasoe MA, von Randow C, Manzi AO, Schafer JS, Eck TF, Holben BN (2006) Effect of smoke and clouds on the transmissivity of photosynthetically active radiation inside the canopy. Atmos Chem Phys 6:1645–1656

Zhang M, Yu GR, Zhang LM, Sun XM, Wen XF, Han SJ, Yan JH (2010) Impact of cloudiness on net ecosystem exchange of carbon dioxide in different types of forest ecosystems in China. Biogeosciences 7:711–722

Zhao L, Li YN, Xu SX, Zhou HK, Gu S, Yu GR, Zhao XQ (2006) Diurnal, seasonal and annual variation in net ecosystem CO_2 exchange of an alpine shrubland on Qinghai–Tibetan plateau. Glob Change Biol 12:1940–1953