

This discussion paper is/has been under review for the journal Biogeosciences (BG).
Please refer to the corresponding final paper in BG if available.

Effects of cloudiness on carbon dioxide exchange over an irrigated maize cropland in northwestern China

B. C. Zhang^{1,2}, J. J. Cao^{1,3}, Y. F. Bai^{2,4}, S. J. Yang⁵, L. Hu⁵, and Z. G. Ning⁶

¹State Key Lab of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China

²Graduate School of the Chinese Academy of Science, Beijing 100049, China

³Department of Environmental Science and Engineering, Xi'an Jiaotong University, Xi'an, 710049, China

⁴Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

⁵College of Agriculture and life sciences, Ankang University, Ankang 725000, China

⁶Shaanxi Changqing National Natural Reserve, Yang County, Shaanxi Province, 723300, China

Received: 10 October 2010 – Accepted: 15 November 2010 – Published: 23 February 2011

Correspondence to: B. C. Zhang (bczhang09@gmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

Clouds can strongly influence solar radiation and affects other microclimatic factors (such as air temperature and vapour pressure deficit), and those changed environmental conditions may exert strong effects on carbon exchange between terrestrial ecosystems and the atmosphere. In this study, we analyzed how canopy photosynthesis and ecosystem respiration respond to changes in cloudy conditions, based on two years of eddy-covariance and meteorological data from an irrigated maize cropland in Yingke oasis of northwestern China. The results showed that net carbon uptake was more negative under cloudy than under clear conditions, it indicates that net carbon uptake increased under cloudy days. The rate of ecosystem respiration (R_e) decreased under cloudy conditions due to decreased air temperature. However, photosynthesis was suppressed by the decreasing air temperature and vapour pressure deficit (VPD) under cloudy skies. Thus, the enhancement of net carbon uptake under cloudy skies mainly contributed from increasing photosynthesis with diffuse radiation. Those results improve our understanding of the effects of cloud cover on carbon exchange process in maize (C4) cropland, and improve our understanding of the driver improving net carbon uptake under cloudy conditions.

1 Introduction

The response of vegetation to the environment is a key global climate change issue, and it has attracted more scientists' attention to how environmental changes influence on net carbon exchange between ecosystems and the atmosphere in recent years (Law et al., 2002; Pingintha et al., 2010). The solar radiation reaching the earth's surface is the primary driver of plant photosynthesis (Mercado et al., 2009). However, clouds, as a natural weather element at a given location, can result in changes in the incident photon flux density and directional quality (diffuse and direct) of sunlight (Gu et al., 1999; Johnson and Smith, 2006). Therefore, the effects of radiation changes associated with

BGD

8, 1669–1691, 2011

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



clouds can improve or depress carbon dioxide (CO₂) exchanges between terrestrial ecosystems and the atmosphere. The previous studies have showed that high CO₂ exchange occurs more frequently on cloudy days instead of clear sky conditions (Gu et al., 1999; Niyogi et al., 2004). However, the impact of clouds is arguably more complicated as terrestrial ecosystem-atmosphere interactions refer to exchanges of heat, moisture, trace gases, aerosols and momentum between land surfaces and the overlying air (Pielke et al., 1998).

Agriculture accounts for nearly 40% of the planet's ice-free land surface and plays an important role in human productivity and life (Ramankutty et al., 2008). Therefore, it is important to measure carbon exchange under clouds to understand the effects of climate change on agricultural ecosystems, and to understand how these systems feedback into the global carbon budget. Since vegetation carbon and water exchanges depend on radiation regimes, the changes in cloud cover may substantially alter ecosystem productivity (Rocha et al., 2004). Over the past few years, there are some attentions paid to the relationship between carbon exchange and cloudy conditions in forest ecosystems (Gu et al., 1999; Zhang et al., 2010; Min and Wang, 2008). Much less attention, however, has been paid to the carbon balance of agroecosystems under cloudy conditions.

Recent studies indicate that there are significant declining trends in clearness index and increasing trends in diffuse ratio in the past 40 years in China (Che et al., 2007). This increase in diffuse radiation is certain to influence the carbon cycles of terrestrial ecosystems. Oases are unique landscapes in arid and semi-arid regions and are the most important parts of arid zones for social and economic development (Zhang et al., 2003). Zhangye agricultural oasis is an important commodity grain production basis and is famous for its high crop production in arid and semi-arid area of north-west China (Chai and Huang, 2005). Therefore, it is essential to unravel how carbon exchange varied under cloud cover, and it could provide us information about the possible trend of net carbon uptake changed in agricultural ecosystems in the future. In this study, our purpose was to investigated how NEE changed under cloudy and clear

BGD

8, 1669–1691, 2011

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



conditions during plant growing season, and determined what factors contributed to these changes.

2 Materials and methods

2.1 Site description

5 Field work was conducted at the Yingke (belongs to Zhangye oasis region) oasis station (100°25' E, latitude 38°51' N, 1519 m a.s.l.) on the middle of Heihe river basin, which is the second largest inner river located in the northwest of China. The study was carried out during the plant growing seasons (June–August) in 2008 and 2009. The annual mean air temperature was 6.5 °C and mean annual precipitation was 125 mm.
10 And the agriculture is supported mostly by the irrigation system. Canopy height was 150–200 cm and maximum leaf area index (LAI) was 3.5–5.2 m⁻² m⁻².

2.2 Eddy covariance and meteorological measurements

Flux of CO₂ was obtained by the eddy-covariance method. The eddy-covariance tower is instrumented with a 3-D sonic anemometer (model CSAT-3, Campbell Sci. Inc., USA) and an open path infrared CO₂ and H₂O gas analyzer (Li-7500, LI-COR Inc., Lincoln, NE, USA). To assure a sufficiently long fetch the eddy-covariance sensors were mounted at 4 m above the ground. The raw high frequency (10 Hz) data was processed to produce half-hourly fluxes of CO₂, water vapour and sensible heat above canopy by using a post processing software of Edire (developed by Edinburgh University, UK).
15 And the records in half-hourly averaged was evaluated for data quality.

Along with the eddy-covariance tower, standard meteorological and soil parameters were measured continuously with an array of sensors. Solar radiation and net radiation was measured with a four component net radiometer (PSP/PIR, Eppley, UAS) 4 m above the ground. Rainfall was measured with a tipping-bucket rain gauge (TE525,

BGD

8, 1669–1691, 2011

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Campbell Sci. Inc., USA). Air humidity and air temperature profiles were measured using shielded and aspirated probes (HMP45C, Vaisala, Finland) at 3 m and 10 m above the canopy. Soil temperature was measured at six different depths with thermometers (107, Campbell Sci. Inc., USA). Soil moisture was monitored with thermocouple sensors (CS616, Campbell Sci. Inc., USA) at the same depth with soil temperature. Incident photosynthetically active radiation (PAR_{tot}) was estimated from solar radiation: PAR_{tot} ($\mu\text{mol photons m}^{-2} \text{s}^{-1}$) = $2.16 \times$ solar radiation (W m^{-2}) (Pingingtha et al., 2010).

2.3 GEP and Re calculations

Net ecosystem exchange of CO_2 relies on the balance between CO_2 uptake through plant photosynthesis and CO_2 emission through plant and soil respiration (ecosystem respiration). The NEE can be measured directly using eddy-covariance methods. Gross ecosystem production (GEP) represents the net rate of carboxylation and oxygenation by the enzyme ribulose biophosphate (Law et al., 2002). GEP was calculated from the difference between daytime NEE and daytime Re ($GEP = Re - NEE$), where a net gain of carbon by the ecosystem is negative in the convention of micrometeorological measurements and Re is positive. Since lacking direct estimation of daytime Re, then based on the assumption that daytime temperature response of Re is the same as the nighttime one, we calculated daytime Re based on the regression equation of nighttime NEE and nighttime air temperature (T_a) under turbulent condition ($U^* > 0.1 \text{ m s}^{-1}$) (Xu and Baldocchi, 2004):

$$NEE_{\text{night}} = b_0 \exp(bT_a) \quad (1)$$

Where b_0 and b are two empirical coefficients.

2.4 Clearness index and diffuse PAR

The clearness index is a veritable tool in characterizing sky conditions over a particular locality (Okogbue et al., 2009). It is defined as the ratio of the global solar radiation (S ,

BGD

8, 1669–1691, 2011

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



$W m^{-2}$) measured at the surface to the total solar radiation (S_e , $W m^{-2}$) at the top of the atmosphere (Gu et al., 1999). It is calculated by follows:

$$CI = \frac{S}{S_e} \quad (2)$$

$$S_e = S_{sc}[1 + 0.033\cos(360t_d/365)]\sin\beta \quad (3)$$

$$\sin\beta = \sin\varphi\sin\delta + \cos\varphi\cos\sigma\cos\omega \quad (4)$$

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

For a given elevation angle, the diffuse components of the solar radiation received by ecosystem could change with cloudiness (Gu et al., 1999; Zhang et al., 2010). Since lacking direct measurements of diffuse PAR, we calculated it based on CI and β . The corresponding equations are described as follows.

$$PAR_{dif} = PAR_{tot} \frac{[1 + 0.3(1 - q^2)]q}{1 + (1 - q^2)\cos^2(90^\circ - \beta)\cos^3\beta} \quad (5)$$

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

Where PAR_{tot} is the total PAR, PAR_{dif} is the diffuse PAR, and S_f is the total diffuse radiation received by horizontal plane on the Earth's surface (Cierco et al., 2007).

3 Results and discussion

3.1 Microclimate conditions

In order to study the carbon exchange between the cropland and the atmosphere, it is necessary to understand the diurnal variation of the key environmental factors. Solar

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



radiation, temperature and VPD greatly impact on carbon uptake. Examples of typical diurnal variation in air temperature, solar radiation and VPD in cropland during the cloudy and cloudless days are presented in Fig. 1. Solar radiation, air temperature and VPD begin increase from 06:00–08:00 h (Beijing Time (the same below)). The maximum solar radiation appeared 14:00 h, while the maximum air temperature and VPD appeared two hours late relative to solar radiation. Solar radiation, air temperature and VPD under clear daytime are higher than those values under cloudy daytime. The diurnal course of air temperature and VPD under cloudy days showed lower extent variation compared with those under clear days.

3.2 Responses of daytime NEE to PAR under clear and cloudy skies

PAR is the main climatic factor that drives photosynthesis processes. To compare how NEE responds to change in PAR under clear and cloudy skies, polynomial function was used to describe the relationship between NEE and PAR (Letts et al., 2005). We can see NEE was more negative under cloudy skies than under clear skies at cropland during the study period (Fig. 2). This indicates that the net carbon uptake increased under cloudy skies. It is consistent with previous research found that higher net CO₂ fluxes on cloudy compared to clear days in grassland and forest ecosystems (Rocha et al., 2004; Law et al., 2002; Zhang et al., 2010; Gu et al., 1999). Almost no light saturation of NEE was observed in this cropland under clear and cloudy skies, which was quite different from what happens in grassland (Jing et al., 2010) and forest ecosystem (Zhang et al., 2010). This could be explained by the characteristics of the cropland, which was cultivated by maize (C₄) and had high PAR requirement related to its higher leaf area index (LAI), above-ground biomass, and single-leaf photosynthetic capacity. The structural characteristics of vegetation canopies, in particular leaf area and light interception capacity, determine the amount of radiant energy absorbed and reflected by the canopy, thus directly affecting rates of photosynthesis (Hanan et al., 2002).

BGD

8, 1669–1691, 2011

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.3 Environment control on GEP and Re in maize cropland

Enhancement of net carbon uptake can be caused by either promoting canopy photosynthesis or decreased leaf and soil respiration. Thus, in order to further examine the dependence of carbon uptake under cloudy intensity and the subsequent changed environment, the response of GEP and Re to changes in the incident PAR were separated into three T_a classes ($T_a > 25^\circ\text{C}$, $20^\circ\text{C} < T_a \leq 25^\circ\text{C}$, and $T_a \leq 20^\circ\text{C}$), and three VPD classes ($\text{VPD} \leq 1 \text{ kPa}$, $1 \text{ kPa} < \text{VPD} \leq 2 \text{ kPa}$, and $\text{VPD} > 2 \text{ kPa}$) at Yingke maize cropland.

The relationship between GEP and total PAR and diffuse PAR are in quadric polynomial function (Fig. 3). GEP increases with total PAR and diffuse PAR, whereas diffuse PAR reached its high value when CI between 0.4–0.6 under cloudy conditions (Fig. 4). Therefore, increased diffuse PAR showed significant beneficial effect on GEP in study site when CI between 0.4–0.6. This range of CI is consistent the range of CI observed in previous studies (Gu et al., 1999; Zhang et al., 2010) in forest ecosystems, but higher than this values observed in short grass over semi-arid regions (Jing et al., 2010). These studies in forest ecosystems showed that NEE reached its maximum net uptake values under cloudy conditions when the value of CI is between 0.4–0.7. While NEE reached its maximum net uptake values when CI of about 0.37, which is lower than the high diffuse PAR occurred (CI in a range 0.5–0.6) in above mentioned grassland. Those results indicated that increased diffuse radiation received by ecosystem is more easily absorbed by shaded leaves for canopy photosynthesis under cloudy conditions (Gu et al., 1999; Oliveira et al., 2007; Alton et al., 2007), but the capability of radiation assimilation are different between different ecosystems. It also suggested that net effect on photosynthesis of radiation changes associated with an increase in clouds or scattering aerosols depends on a balance between the reduction in total 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).

Irrespective of T_a , GEP increased with increasing PAR for all temperature conditions, and it increased more obvious at low levels of PAR (Fig. 5). The light saturation point at

BGD

8, 1669–1691, 2011

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



cropland ($1500 \mu\text{mol quantum m}^{-2} \text{s}^{-1}$ at $T_a \leq 20^\circ\text{C}$ and $1800 \mu\text{mol quantum m}^{-2} \text{s}^{-1}$ at $T_a > 25^\circ\text{C}$) are higher than those reported in grassland and forest ecosystems (Zhan et al., 2007; Zhang et al., 2010). Canopy photosynthesis under high temperature range ($T_a > 25^\circ\text{C}$) was higher than the lower temperature ranges. It can be seen from Fig. 5 that the cropland had high capacity for CO_2 assimilation under high temperature and high PAR levels. It indicates that the C4 plant of maize have a much higher optical temperature and PAR to canopy photosynthesis. There is large evidence of the greater photosynthetic capacity of C4 compared to C3 species (Crafts-Brandner and Salvucci, 2002). Previous research observed that net photosynthesis was inhibited at leaf temperatures above 38°C for C4 plant (Crafts-Brandner and Salvucci, 2002). While the maximum temperature at the Yingke maize site is no more than 35°C , therefore, which below the level of ultimate limitation to CO_2 fixation for photosynthesis.

Previous research had demonstrated that VPD is an important factor in regulating net photosynthesis and stomatal conductance (Poulson et al., 2002; Shirke and Pathre, 2004) of many species. The role of stomata in regulating the exchange of CO_2 for water is central to many plant and ecosystem processes, services and products. In order to examine how GEP varied under cloudy conditions, we also compared GEP responses to PAR under three VPD levels. In our study, the optimum VPD for GEP appeared in the high level VPD ($\text{VPD} > 2 \text{ kPa}$) (Fig. 6). This results is consistent with the observed data in subtropical evergreen broad-leaved forest at Dinghushan, but the VPD value is bigger than it was observed in temperate broad-leaved Korean pine mixed forest at Changbaishan (Zhang et al., 2010), and grassland cropland ecology in semiarid inner Mongolia (Zhan et al., 2007). It may be different ecosystem with different respond to VPD. Our purpose is to examine how VPD impact on carbon exchange under cloudy conditions, thus we examine the relationship between VPD and clearness index. For a given solar elevation angle, VPD reduced linearly with decreasing CI (Fig. 7). Therefore, we can confirm that the decrease in VPD associated with cloudy conditions can decrease canopy photosynthesis in Yingke maize cropland.

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Although the plotted values showed a larger scatter, the regression curve showed that respiration decreased as decreasing temperature (Fig. 8). It is consistent with previous researches observed that soil respiration responds positively to temperature (Xu and Baldocchi, 2004; Shi et al., 2006). In addition, we also examined the relationship between air temperature and clearness index, and found positive relationship between them (Fig. 9). Therefore, we can confirm that ecosystem respiration decreased under cloudy conditions. As discussed above, the decreased in temperature for cloud cover can also depress canopy photosynthesis. We extended the analysis of the relationship between NEE and air temperature in short-term period, linear relationship was fit to describe their relationship (Fig. 10). It suggests that canopy photosynthesis was more sensitive to temperature than respiration. This result is not consistent with previous observations showed that respiration is highly sensitive to temperature while photosynthesis is relatively insensitive (Albrizio and Steduto, 2003; Amthor, 1989). Thus, under the cloudy conditions an decreased contribution of temperature to net carbon exchange in this cropland.

4 Conclusions

We quantified NEE and its response to cloudiness over C4 maize cropland in Yingke oasis using the eddy-covariance technique during growing season (June–August) from 2008 to 2009. As observed, NEE response to PAR was more negative under cloudy skies than under clear skies. It indicates that net carbon uptake increased under cloudy conditions. We found that air temperature and VPD decrease under cloudy skies in Yingke cropland, which can depress carbon photosynthesis. The ecosystem respiration decreased due to decreased air temperature. However, increasing diffuse PAR caused by cloudiness could significantly increase the carbon uptake. Therefore, we can confirm that the increasing net carbon uptake under cloudy skies is mainly contributed from the increasing diffuse PAR.

Acknowledgements. This study is supported by the China eleventh five-year plan science and technology support project (2007BAC30B00), and it has been (partially) also supported by the European Commission (Call FP7-ENV-2007-1 Grant nr. 212921) as part of the CEOP – AEGIS project (HHUU <http://www.ceop-aegis.org/> UUHH) coordinated by the Université Louis Pasteur, and by the Chinese Academy of Sciences Action Plan for West Development Project “Watershed Allied Telemetry Experimental Research” (grant number KZCX2-XB2-09).

References

- Albrizio, R. and Steduto, P.: Photosynthesis, respiration and conservative carbon use efficiency of four field grown crops, *Agric. For. Meteorol.*, 116, 19–36, 2003.
- Alton, P. B., North, P. R., and Los, S. O.: The impact of diffuse sunlight on canopy light-use efficiency, gross photosynthetic product and net ecosystem exchange in three forest biomes, *Global Change Biol.*, 13, 776–787, 2007.
- Amthor, J. S.: *Respiration and crop productivity*, Springer, New York, 215, 1989.
- Chai, Q. and Huang, G. B.: Current situation and optimize tactics of population-arable land-grain system in oasis irrigation area-Taking Ganzhou district of Zhangye as an example, *Journal of Gansu Agricultural University*, 4, 566–570, 2005 (in Chinese).
- Che, H. Z., Shi, G. Y., Zhang, X. Y., Zhao, J. Q., and Li, Y.: Analysis of sky conditions using 40 year records of solar radiation data in China, *Theor. Appl. Climatol.*, 89, 83–94, 2007.
- Cierco, F.-X., Naaim-Bouvet, F., and Bellot, H.: Acoustic sensors for snowdrift measurements: How should they be used for research purposes?, *Cold Reg. Sci. Technol.*, 49, 74–87, 2007.
- Crafts-Brandner, S. J. and Salvucci, M. E.: Sensitivity of photosynthesis in a C4 plant, maize, to heat stress, *Plant Physiol.*, 129, 1773–1780, 2002.
- Gu, L. H., Fuentes, J. D., Shugart, H. H., Staebler, R. M., and Black, T. A.: Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: Results from two North American deciduous forests, *J. Geophys. Res.-Atmos.*, 104(D24), 31421–31434, doi:10.1029/1999JD901068, 1999.
- Hanan, N. P., Burba, G., Verma, S. B., Berry, J. A., Suyker, A., and Walter-Shea, E. A.: Inversion of net ecosystem CO₂ flux measurements for estimation of canopy PAR absorption, *Global Change Biol.*, 8, 563–574, 2002.
- Jing, X., Huang, J., Wang, G., Higuchi, K., Bi, J., Sun, Y., Yu, H., and Wang, T.: The ef-

BGD

8, 1669–1691, 2011

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



fects of clouds and aerosols on net ecosystem CO₂ exchange over semi-arid Loess Plateau of Northwest China, *Atmos. Chem. Phys.*, 10, 8205–8218, doi:10.5194/acp-10-8205-2010, 2010.

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

Law, B. E., Falge, E., Gu, L., Baldocchi, D. D., Bakwin, P., Berbigier, P., Davis, K., Dolman, A. J., Falk, M., Fuentes, J. D., Goldstein, A., Granier, A., Grelle, A., Hollinger, D., Janssens, I. A., Jarvis, P., Jensen, N. O., Katul, G., Mahli, Y., Matteucci, G., Meyers, T., Monson, R., Munger, W., Oechel, W., Olson, R., Pilegaard, K., Paw, K. T., Thorgeirsson, H., Valentini, R., Verma, S., Vesala, T., Wilson, K., and Wofsy, S.: Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation, *Agric. For. Meteorol.*, 113, 97–120, 2002.

Letts, M. G., Lafleur, P. M., and Roulet, N. T.: On the relationship between cloudiness and net ecosystem carbon dioxide exchange in a peatland ecosystem, *Ecoscience*, 12, 53–59, 2005.

Mercado, L. M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M., and Cox, P. M.: Impact of changes in diffuse radiation on the global land carbon sink, *Nature*, 458, 1014–U1087, 2009.

Min, Q. L. and Wang, S. Y.: Clouds modulate terrestrial carbon uptake in a midlatitude hardwood forest, *Geophys. Res. Lett.*, 35, L02406, doi:10.1029/2007gl032398, 2008.

Niyogi, D., Chang, H. I., Saxena, V. K., Holt, T., Alapaty, K., Booker, F., Chen, F., Davis, K. J., Holben, B., Matsui, T., Meyers, T., Oechel, W. C., Pielke, R. A., Wells, R., Wilson, K., and Xue, Y. K.: Direct observations of the effects of aerosol loading on net ecosystem CO₂ exchanges over different landscapes, *Geophys. Res. Lett.*, 31, L20506, doi:10.1029/2004gl020915, 2004.

Okogbue, E. C., Adedokun, J. A., and Holmgren, B.: Hourly and daily clearness index and diffuse fraction at a tropical station, Ile-Ife, Nigeria, *Int. J. Climatol.*, 29, 1035–1047, 2009.

Oliveira, P. H. F., Artaxo, P., Pires, C., De Lucca, S., Procopio, A., Holben, B., Schafer, J., Cardoso, L. F., Wofsy, S. C., and Rocha, H. R.: The effects of biomass burning aerosols and clouds on the CO₂ flux in Amazonia, *Tellus Ser. B*, 59, 338–349, 2007.

Pielke, R. A., Avissar, R., Raupach, M., Dolman, A. J., Zeng, X. B., and Denning, A. S.: Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate, *Global Change Biol.*, 4, 461–475, 1998.

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Pingintha, N., Leclerc, M. Y., Beasley Jr., J. P., Durden, D., Zhang, G., Senthong, C., and Rowland, D.: Hysteresis response of daytime net ecosystem exchange during drought, *Biogeosciences*, 7, 1159–1170, doi:10.5194/bg-7-1159-2010, 2010.
- 5 Poulson, M. E., Edwards, G. E., and Browse, J.: Photosynthesis is limited at high leaf to air vapor pressure deficit in a mutant of *Arabidopsis thaliana* that lacks trienoic fatty acids, *Photosynth. Res.*, 72, 55–63, 2002.
- Ramankutty, N., Evan, A. T., Monfreda, C., and Foley, J. A.: Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000, *Global Biogeochem. Cycles*, 22, GB1003, doi:10.1029/2007gb002952, 2008.
- 10 Rocha, A. V., Su, H. B., Vogel, C. S., Schmid, H. P., and Curtis, P. S.: Photosynthetic and water use efficiency responses to diffuse radiation by an aspen-dominated northern hardwood forest, *Forest Sci.*, 50, 793–801, 2004.
- Shi, P. L., Zhang, X. Z., Zhong, Z. M., and Ouyang, H.: Diurnal and seasonal variability of soil CO₂ efflux in a cropland ecosystem on the Tibetan Plateau, *Agric. For. Meteorol.*, 137, 220–233, 2006.
- 15 Shirke, P. A. and Pathre, U. V.: Influence of leaf-to-air vapour pressure deficit (VPD) on the biochemistry and physiology of photosynthesis in *Prosopis juliflora*, *J. Exp. Bot.*, 55, 2111–2120, 2004.
- Xu, L. K. and Baldocchi, D. D.: Seasonal variation in carbon dioxide exchange over a Mediterranean annual grassland in California, *Agric. For. Meteorol.*, 123, 79–96, 2004.
- 20 Zhan, W. L., Chen, S. P., Chen, J., Wei, L., Han, X. G., and Lin, G. H.: Biophysical regulations of carbon fluxes of a steppe and a cultivated cropland in semiarid Inner Mongolia, *Agric. For. Meteorol.*, 146, 216–229, 2007.
- Zhang, H., Wu, H. W., Zheng, Q. H., and Yu, Y. H.: A preliminary study of oasis evolution in the Tarim Basin, Xinjiang, China, *J. Arid. Environ.*, 55, 545–553, 2003.
- 25 Zhang, M., Yu, G.-R., Zhang, L.-M., Sun, X.-M., Wen, X.-F., Han, S.-J., and Yan, J.-H.: Impact of cloudiness on net ecosystem exchange of carbon dioxide in different types of forest ecosystems in China, *Biogeosciences*, 7, 711–722, doi:10.5194/bg-7-711-2010, 2010.

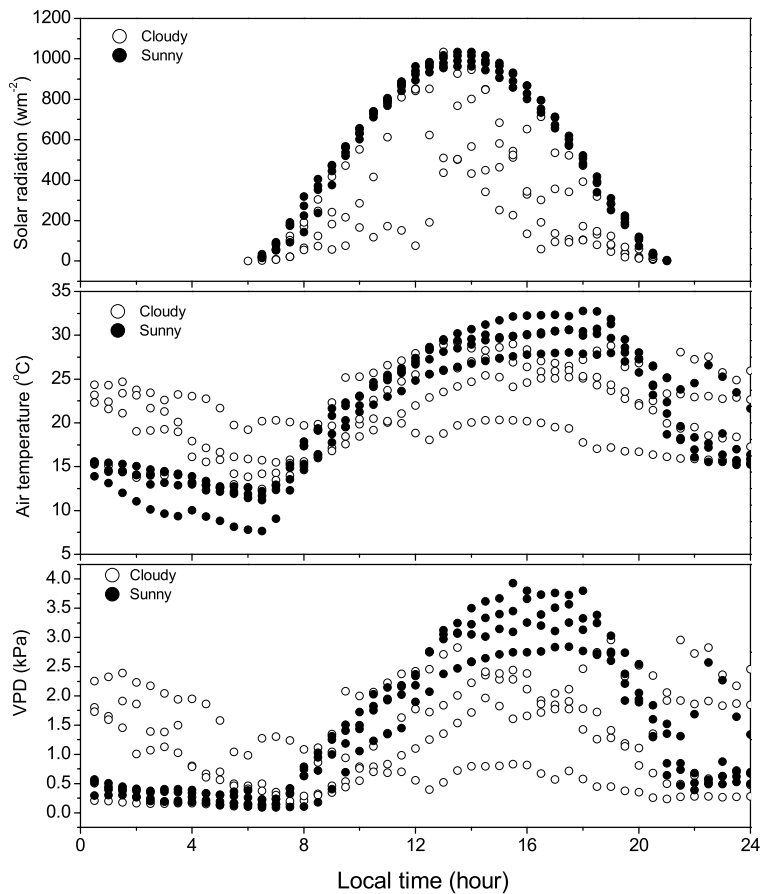


Fig. 1. Diurnal variations of solar radiation, air temperature, vapor pressure deficit (VPD) under clear and cloudy days.

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

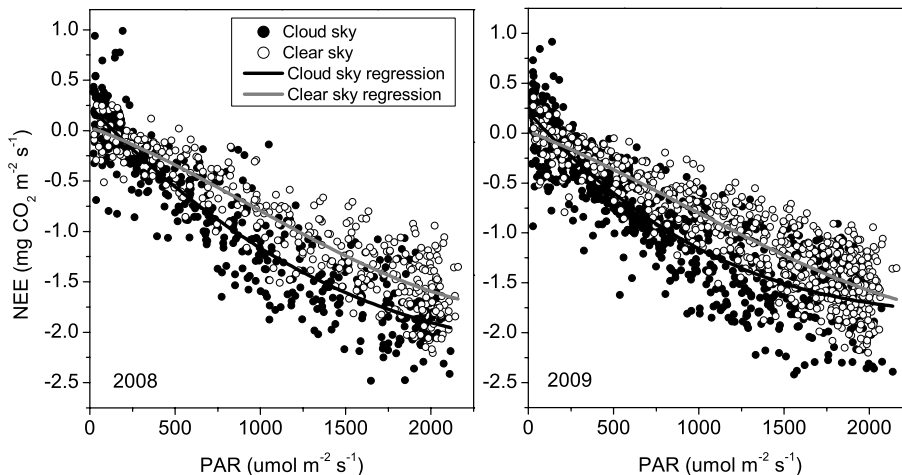


Fig. 2. Response of NEE to PAR during growth season (June–August) from 2008 to 2009 under clear and cloudy days at Yingke maize cropland.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

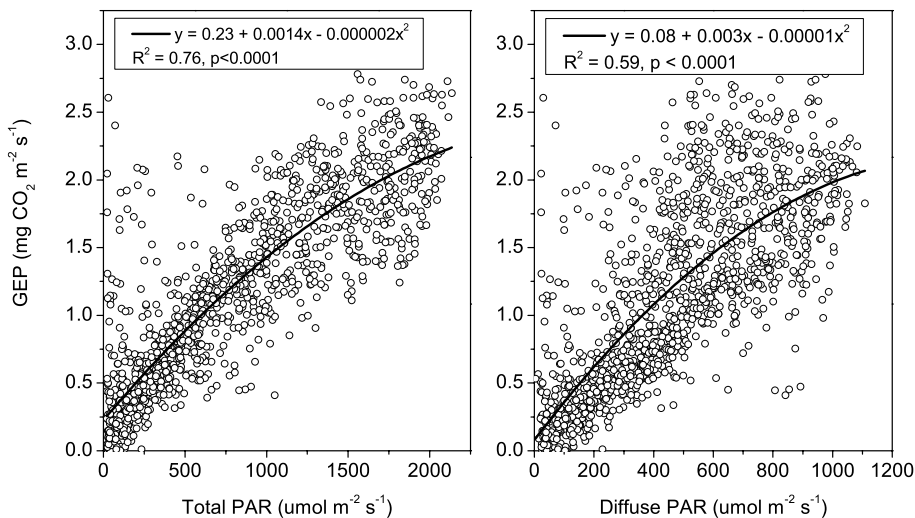


Fig. 3. Response of GEP to total PAR and diffuse PAR under cloudy days at Yingke maize cropland.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

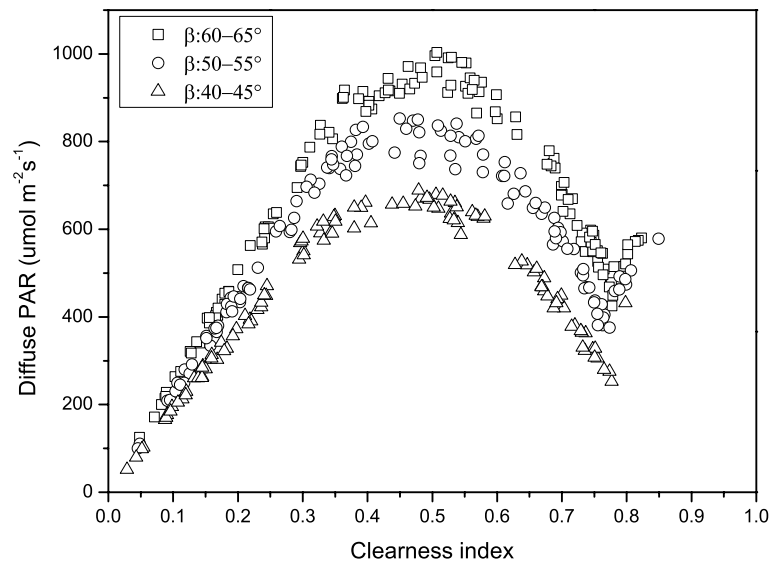


Fig. 4. Changes of diffuse PAR with clearness index (CI) for selected intervals of solar elevation angles during the study period.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

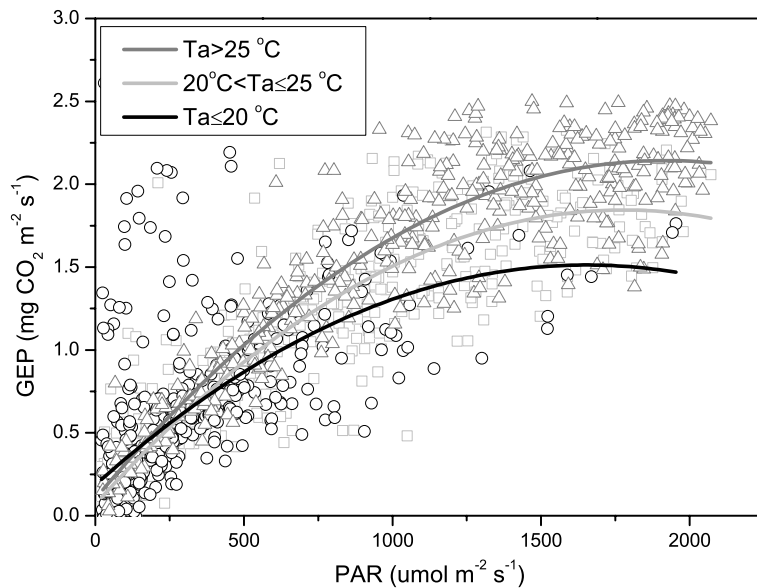


Fig. 5. The response of GEP to PAR under different level of air temperature (T_a).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



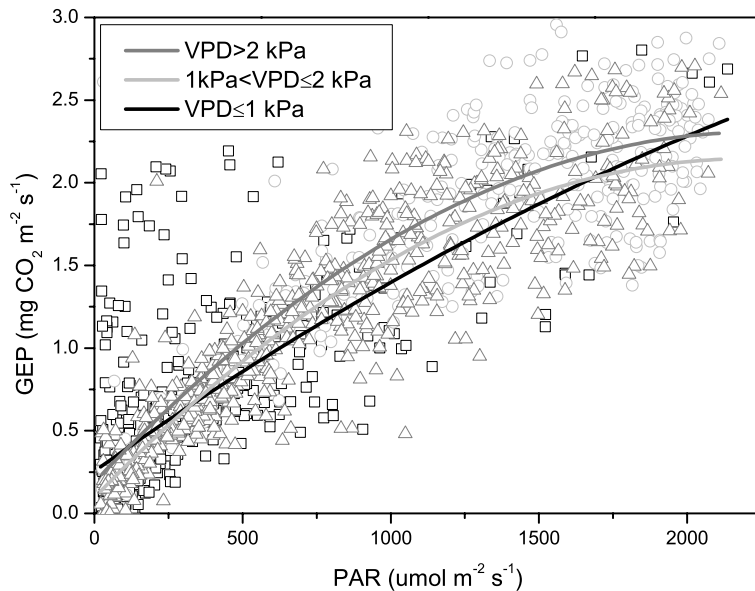


Fig. 6. The response of GEP to PAR under different level of vapor pressure deficit (VPD).

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

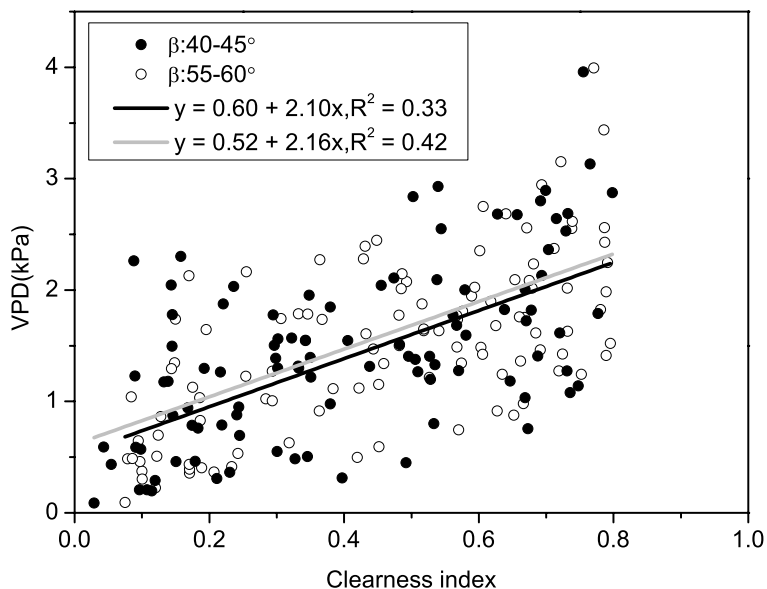


Fig. 7. Changes of vapor pressure deficit (VPD) with clearness index (CI) for selected intervals of solar elevation angles during the study period.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



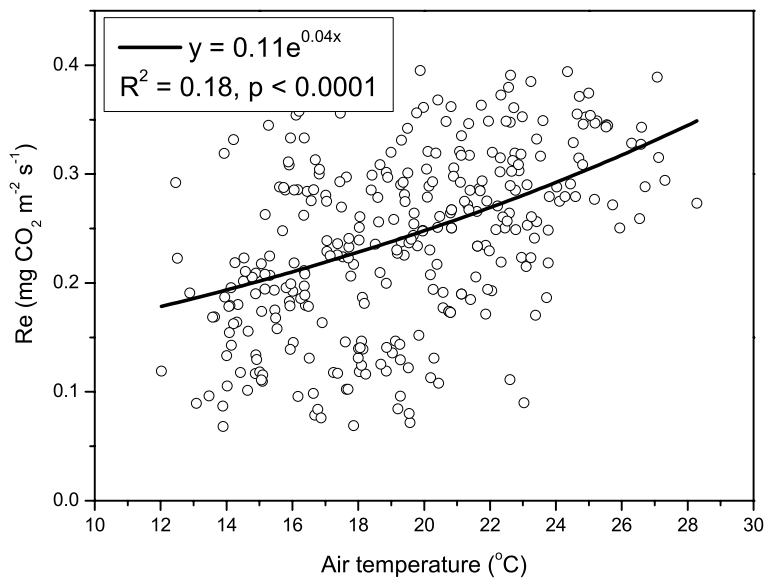


Fig. 8. The relationship between nighttime NEE (Re) and air temperature during the study period.

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

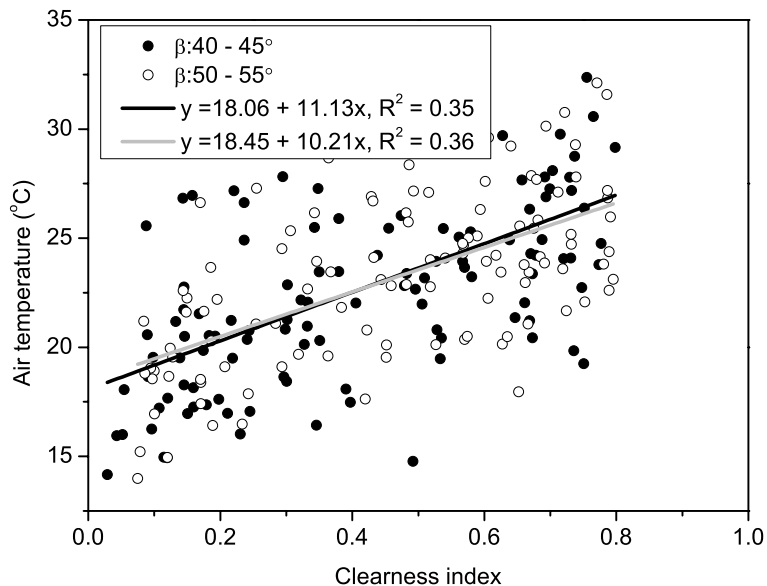


Fig. 9. Changes of air temperature (T_a) with clearness index (CI) for selected intervals of solar elevation angles during the study period.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



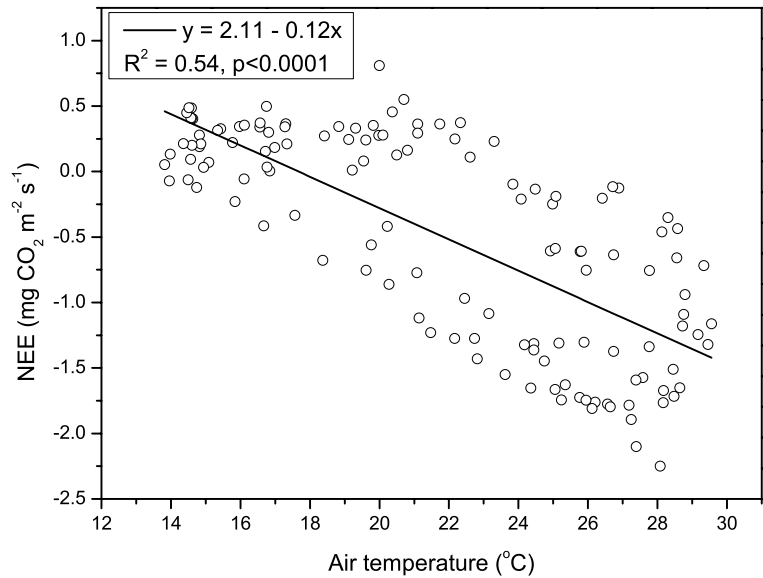


Fig. 10. The relationship between NEE and air temperature in short-term period.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

BGD

8, 1669–1691, 2011

Effects of cloudiness on carbon dioxide exchange

B. C. Zhang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

