GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L02406, doi:10.1029/2007GL032398, 2008

Clouds modulate terrestrial carbon uptake in a midlatitude hardwood forest

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Received 18 October 2007; revised 30 November 2007; accepted 12 December 2007; published 29 January 2008.

Citation: Min, Q., and S. Wang (2008), Clouds modulate terrestrial carbon uptake in a midlatitude hardwood forest, *Geophys. Res. Lett.*, *35*, L02406, doi:10.1029/2007GL032398.

[1] Thirteen years of turbulent exchange and radiation measurements in a midlatitude hardwood forest show that clouds enhance radiation use efficiency of carbon uptake (RUE), and that maximum carbon uptake occurs under moderate cloud cover. We find that both cyclic and secular variability of a simple observable metric of cloudiness (transmittance index) is the best statistical predictor of the interannual variability of both net ecosystem production (NEP) and gross ecosystem production (GEP) seen in our dataset. In contrast other factors analyzed show much weaker relationships with the terrestrial carbon uptake. This suggests that clouds play a pivotal role in driving the interannual variability of terrestrial carbon uptake by this forest and are an important mechanism of carbon cycle/climate interaction.

[2] The interannual variability in the growth rate of atmospheric CO_2 is modulated significantly by terrestrial ecosystem processes [*Houghton*, 2000]. The interaction of climate with regional characteristics of ecosystems imposes complex controlling factors on carbon uptake in different vegetation and climate regimes around the world [*Churkina and Running*, 1998; *Nemani et al.*, 2003; *Barford et al.*, 2001]. Recent studies suggest that climate change, along with alteration of CO_2 fertilization, nitrogen deposition and land-use characteristics, alters the global terrestrial ecosystem through several controlling factors in terrestrial carbon uptake (e.g., temperature [*Braswell et al.*, 1997; *Lucht et al.*, 2000], precipitation [*Nemani et al.*, 2002], and radiation [*Nemani et al.*, 2003; *Gu et al.*, 2003]). However, the presence of clouds can both cause, and be the consequence of, changes in these controls, and subsequent impacts on stomatal dynamics through changes in leaf temperature and leaf-to-air water vapor pressure deficit (WVPD) [*Min*, 2005].

[3] Total cloud cover has increased about 2% over many mid- to high-latitude land areas since the beginning of the 20th Century [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. The increase in total cloud amount, combined with secondary damping effects through soil moisture and precipitation, affects surface temperatures and is negatively correlated with diurnal temperature ranges [*Dai et al.*, 1997]. Clouds also strongly affect the geographic patterns of diurnal temperature range [*Dai et al.*, 1999]. Moreover, changes in precipitation in mid- and high-latitudes over land have a strong correlation with long-term changes in total cloud amount [*IPCC*, 2001]. Clouds also modulate solar radiation and photosynthetically-active radiation (PAR) to favour photosynthesis by changing the spectral distribution (light "spectral quality") and diffuse fraction [*Min*, 2005] and alter stomatal dynamics in fluctuating light environments [*Fitzjarrald et al.*, 1995]. Observational evidence shows that carbon uptake by plants is enhanced on days when the diffuse component of PAR is augmented by clouds or aerosols [*Gu et al.*, 2003; *Min*, 2005; *IPCC*, 2001; *Hollinger et al.*, 1994; *Price and Black*, 1990; *Fan et al.*, 1995; *Gu et al.*, 1999; *Freedman et al.*, 2001; *Gu et al.*, 2002; *Niyogi et al.*, 2004].

[4] Clouds are linked to key factors of climate variability, but their role in the interannual variation of terrestrial CO_2 exchange on ecosystem or larger scales has received relatively little attention. Here we examine interannual variability of temperature, precipitation, and cloud distribution and their effects on carbon uptake by analyzing long term turbulent CO_2 exchange and radiation measurements from 1992 to 2004 at a northern hardwood forest (Harvard Forest, 42.5N, 72.2W) [*Wofsy et al.*, 1993] (see http://harvardforest.fas.harvard.edu/). The net ecosystem production (NEP) was computed based on the eddy correlation measurements of carbon uptake [*Wofsy et al.*, 1993]. The gross ecosystem production (GEP) was calculated by subtracting respiration (RESP) from NEP, where respiration was measured directly at night and extrapolated for daytime on the basis of day-night changes in soil temperature [*Barford et al.*, 2001; *Goulden et al.*, 1996; *Wofsy et al.*, 1993].

[5] We use the atmospheric transmittance index (TI) as a measure of cloudiness and aerosol loading, as derived from measured surface shortwave radiation after removing dependences of solar zenith angle and solar distance. Radiation impacts due to changes in aerosol and water vapor are relatively smaller than those due to changes in cloud fraction and optical properties. Thus, TI can be viewed as a measure of clouds with the combined effect of both cloud fraction and cloud optical depth, directly linking to the surface cloud forcing defined by *Betts and Viterbo* [2005]. A smaller TI is produced by a larger cloud/aerosol optical depth or a greater cloud cover or a combined effect of cloud cover and cloud optical depth in partly cloudy conditions (see auxiliary material).[1]

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0094-8276/08/2007GL032398$05.00

[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL032398.

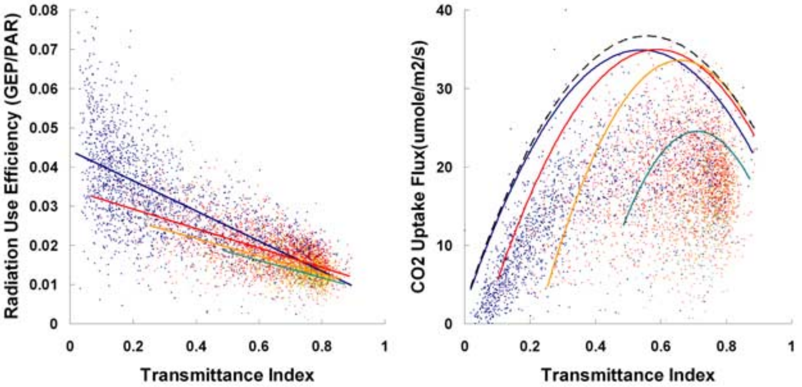

Figure 1. (left) Radiation use efficiencies and (right) carbon uptake fluxes as a function of TI during the summer season (JJA) from 1992 to 2004 for four WVPD bins: blue, red, orange, and green dots represent data with ranges of WVPD of 0 hPa < WVPD < 4 hPa, 4 hPa $\leq$ WVPD < 12 hPa, 12 hPa $\leq$ WVPD < 16 hPa, and WVPD $\geq$ 16 hPa, respectively. The corresponding color lines are a linear regression for RUE and a quadratic regression for maximum carbon uptake for various WVPD ranges. The dashed-black line in right plot shows the best fit of CO2 uptake flux for all WVPD conditions.

[6] Clouds have two competing effects on radiation: reduction of direct beam radiation and enhancement of diffuse radiation with altered spectral distribution. Diffuse radiation provides a favorable spectral distribution for photosynthesis and penetrates canopies more efficiently than direct beam radiation, thereby enhancing the radiation use efficiency (RUE) [*Min*, 2005]. Furthermore, the presence of clouds reduces leaf temperature and increases relative humidity (RH) in the forest, thus decreasing WVPD and stimulating carbon uptake. The near-surface relative humidity, as a consequence of the boundary layer equilibrium, is directly linked to the lifting condensation levels and thus is an indication of the cloud-base height. To separate the coupled effects of clouds on carbon uptake, hourly CO_2 uptake (FCO_2) as measured by eddy-correlation and radiation use efficiency (ratio of GEP to downwelling PAR) are binned by four different ranges of WVPD: 0–4 hPa, 4–12 hPa, 12–16 hPa, and >16 hPa (Figure 1). The selection of binning classes for WVPD is somewhat arbitrary: 0–4 hPa for extreme moisture regimes; 4–12 hPa for normal regimes; 12–16 hPa for normal dry regimes; and >16 hPa for semi-arid and dry regimes. From Figure 1 it is apparent that WVPD is modulated by clouds, as a consequence of climate-ecosystem interaction. The bin with a lower WVPD has a smaller mean value of TI with a larger variation of TI. In extremely dry conditions, the atmosphere has fewer clouds with high values of TI. For a given range of WVPD, the RUE increases with decreasing TI or increasing cloud amount due to the effect of clouds on photosynthesis. This is consistent with the previous finding at Harvard Forest site that the RUE of carbon uptake increases by 39% and 57% from clear-sky (aerosols) to patchy/thin clouds and optically thick clouds, respectively [*Min*, 2005]. The mean RUE in each WVPD bin increases with decreasing WVPD, as values changes from 0.013, 0.014, 0.016, to 0.025, due to a low WVPD increasing stomatal conductance and stimulating photosynthesis. More importantly, the slope of a linear regression between RUE and TI in each WVPD bin also decreases from −0.0222, −0.0224, −0.0249, −0.0380 with decreasing WVPD, respectively, indicating clouds have more profound impacts on carbon uptake when the WVPD is low. Furthermore, a quadratic regression with both cloudiness, TI, and humidity, WVPD, to RUE has a correlation coefficient (R^2) of 0.658. This is the most significant regression among various parameter combinations we tested (more details of multi-regression analysis and principal component analysis in auxiliary material). Combining RH, an indicator of cloud base height, and TI, the correlation coefficient (R^2) of a quadratic regression to RUE is 0.657, almost identical to that using a traditional humidity parameter, WVPD. It illustrates cloud conditions are most important factors in controlling RUE. The ratio of NEP to PAR has similar characteristics to RUE, except for vary small TIs for the lowest WVPD bin (Figure S4a). Under such conditions, soil moisture was very high and PAR radiation was small and varied around the compensation point of photosynthesis, resulting in substantial enhancement of the ratio of respiration to PAR (Figure S4b).

[7] The trade off between reduced total radiation and a higher RUE under cloudy conditions results in a maximum of canopy carbon uptake at intermediate values of TI and reduction of carbon uptake at both ends of the TI distribution (Figure 1 (right)). The maximum of carbon sequestration is a consequence of the interaction of climate with regional vegetation characteristics. The optimal cloud conditions and the maximum carbon uptake change for various WVPD conditions, as shown in Figure 1 (right). Using WVPD as an indicator of climate-vegetation characteristics, the cloud impact and maximum carbon uptake, the combined effect of radiation and RUE, vary significantly from region to region. Furthermore, the optimal cloudiness for carbon uptake for each WVPD bin divides potential carbon uptake into two regimes: a cloud enhanced carbon uptake regime and a cloud suppressed carbon uptake regime. There is a positive relation between carbon sequestration and cloudiness when climate-driven variability of clouds varies within the cloud enhanced carbon uptake regime. The reverse is true in the cloud suppressed carbon uptake regime.

[8] Interannual variations of carbon uptake reflect the interaction of climate with regional ecosystems. Phenolog-

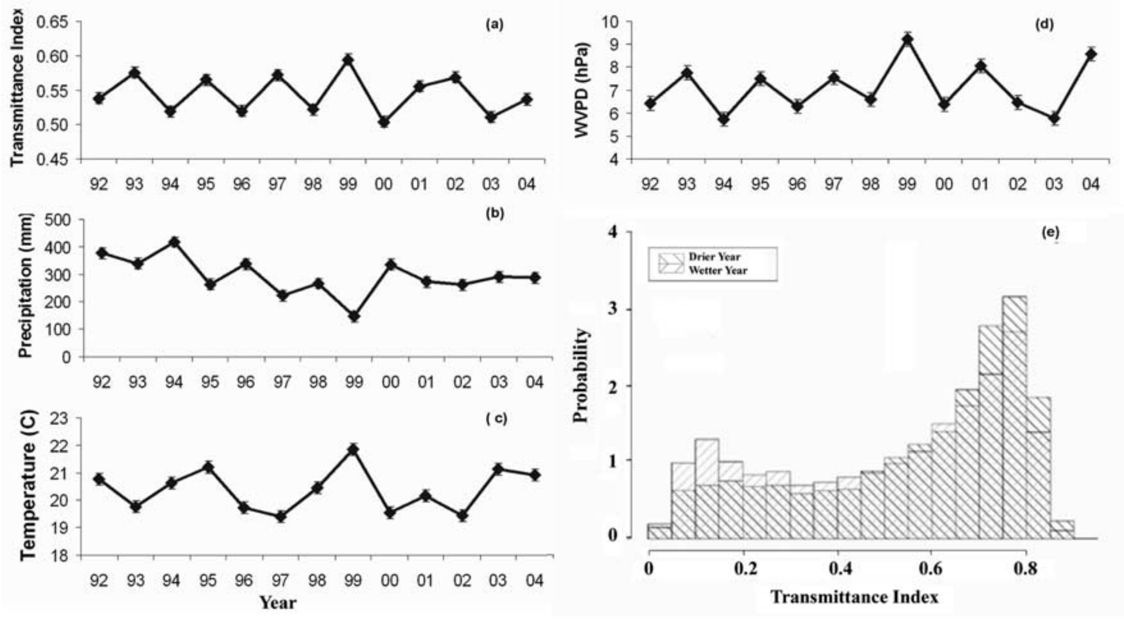

Figure 2. Time series of mean values and variances for (a) TI, (b) precipitation, (c) temperature, and (d) WPVD during the midsummer (JJA) growing season from 1992 to 2004. (e) The distributions of averaged TI for both less humid years and more humid years.

ical characteristics, especially bud burst, leaf expansion, and leaf senescence, are responsive to temperature and precipitation in spring and autumn. Earlier springs and wetter autumns over the last two decades have resulted in a lengthening of the vegetation carbon uptake period that could account for a large fraction of the increase in observed forest growth rates [*Nemani et al.*, 2003; *Goulden et al.*, 1996]. To exclude periods of leaf emergence and senescence, we focus on the midsummer growing season from June to August when the canopy is fully mature. On-site observation and the remotely-sensed vegetation index confirm that the vegetation state features little variation during this period. Interannual variation of vegetation indices is relatively small [*Sakai et al.*, 1997; *Min and Lin*, 2006].

[9] To understand the controlling factors on ecosystem exchange at interannual time scales, we average TI, precipitation and temperature during the midsummer growing season (June, July, and August) for each year from 1992 to 2004 (Figure 2). To emphasize photosynthesis, we use only daytime (solar zenith angle <70°) measurements of temperature and TI to evaluate summer means. To limit invalid or missing measurement periods of precipitation which may skew the total precipitation, we use averaged precipitation during the growing season over valid days. We further correlate these averaged controlling factors with averaged NEP, GEP, and RESP for the corresponding periods.

[10] Local climate is modulated by the interannual variability of the large scale circulations such as the El Niño/Southern Oscillation (ENSO) and the Quasi-Biennial Oscillation (QBO) [*Hashimoto et al.*, 2004; *Pascoe et al.*, 2005]. Clouds are influenced strongly by interaction of the large scale circulation with local ecosystem characteristics. Time series of TI show a Quasi-Biennial Oscillation (Figure 2a), which may relate with the QBO of equatorial zonal wind [e.g., *Pascoe et al.*, 2005, Figure 8a]. Years in the easterly phase of the QBO have smaller mean values of TI with larger variances of TI distributions than years in the westerly phase of the QBO (Figure 2e). These years also have a distinct second peak at TI of 0.18 and higher percentages of thick clouds than years in the westerly phase. Years in the westerly phase, on the other hand, have more thin or broken clouds with higher mean values of TI. Precipitation is strongly associated with thick clouds, resulting in a corresponding oscillation in time series of precipitation (Figure 2b). However, temperature measured at the top of canopy (27.9 m) shows a different variation from clouds and precipitations (Figure 2c). In response to the interannual variation of clouds, moisture in the forest also shows a strong quasi-biennial oscillation (lower WVPD during the more cloudy growing seasons and higher WVPD in less cloudy years; Figure 2d).

[11] To understand the affect of clouds on inter-annual variability in carbon cycle processes, it is necessary to analyze the influences of both cyclic phenomena and secular changes in cloud variations. We therefore separate our dataset into two groups: more humid years and less humid years, corresponding to different phases of the quasi-biennial oscillation of TI and WVPD. NEP and TI have correlation coefficients (R^2) of 0.66 and 0.80 for more humid years and less humid years, respectively (Figure 3). Statistics for Figure 3 are listed in Tables 1a and 1b. Given summer mean values of TI from 0.47 to 0.59 (mean TIs vary within the cloud enhanced carbon uptake regime at Harvard Forest site), each phase exhibits enhancement of NEP with an increase of clouds (decreasing TI) despite a reduction of total PAR reaching the forest. As mentioned previously and shown in Figure 2e, the less humid years have a smaller percentage of thick clouds and a larger percentage of modest clouds (thin or broken). As the photosynthesis processes respond favourably to intermediate clouds (Figure 1), NEP in the less humid years are substantial

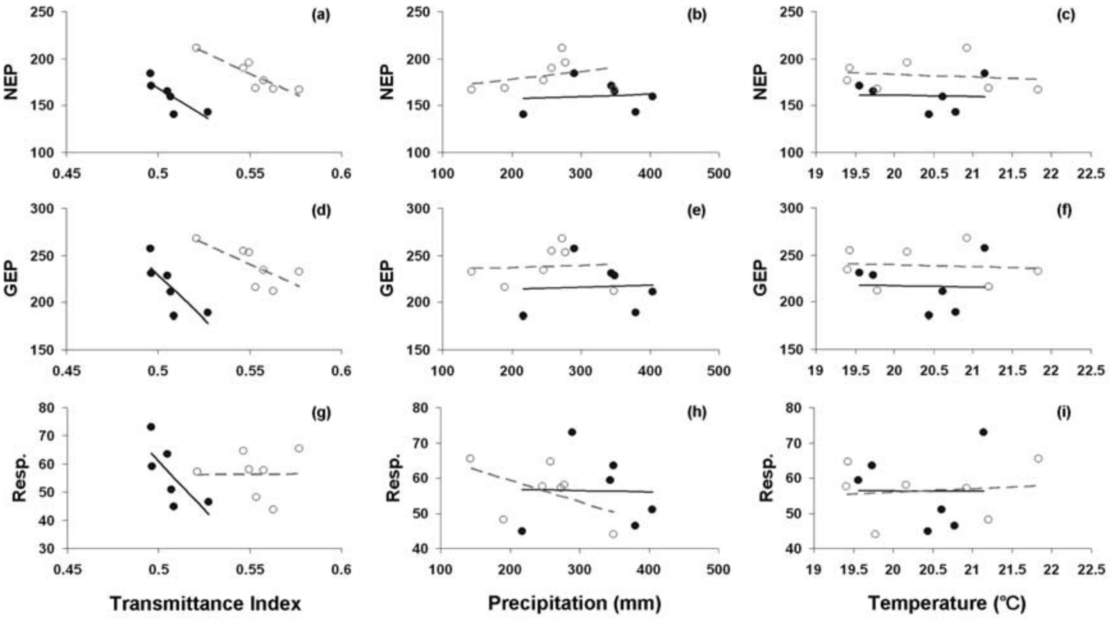

Figure 3. Scatterplots of NEP (unit: KgC/day/ha), GEP (unit: KgC/day/ha), and RESP (unit:KgC/day/ha) as functions of transmittance index, precipitation, and temperature for the midsummer growing season (JJA) from 1992 to 2004. Blue dots are for more humid years (1992, 1994, 1996, 1998, 2000, 2003), and red open circles are for less humid years (1993, 1995, 1997, 1999, 2001, 2002).

higher than in the more humid years given the same mean value of TI. The slope for the linear fit of the more humid phase, −1178, is 33% steeper than the slope for the less humid phase (−884.94), indicating cloud modulation of NEP is more significant in the more humid years than in the less humid years, which is consistent with the previous finding.

[12] Precipitation enhances carbon uptake as shown in Figure 3b for less humid phases, as rainfall increases or maintains the soil moisture and reduces water stress on the ecosystem [*Nemani et al.*, 2002]. NEP has no statistically-significant relationship with mean temperature during midsummer growing season (Figure 3c). The correlation coefficients for the two controlling factors are much smaller than that of TI (Tables 1a and 1b) and too small to be statistically-significant. These slight correlations may be in part due to mediation of precipitation and temperature on carbon uptake or because of the presence of clouds that modulate precipitation and temperature.

[13] Like NEP, GEP has a strong linear relationship with TI in each phase (Figure 3d). With an increase of cloudiness the difference of cloud characteristics between the two phases becomes smaller, decreasing the difference of GEP. The difference of GEP further diminishes when cloudiness reaches a critical point of 0.45. There are no statistically-significant correlations of GEP with either temperature or precipitation in 13-year long measurements (Figures 3e–3f). Respiration in general depends on soil temperature and soil moisture [*Savage and Davidson*, 2001]. For the more humid years, the respiration increases with cloudiness (decreasing of TI) as soil moisture is maintained in response to thick clouds and decreased evapotranspiration (Figure 3g) and lower WVPDs. For less humid years, respiration apparently increases with TI but this relationship is statistically insignificant. Nor does the respiration correlate with precipitation and canopy temperature for both more humid and less humid phases (Figure 3h–3i).

[14] The above analysis demonstrates that clouds, their mean properties as reflected in the TI values, and their distribution are the most important climatic factors in driving the interannual variability of the terrestrial carbon uptake during the growing season. We further analyze the interannual variability of the entire growing season, including early spring and late autumn (auxiliary material). A similar conclusion was found with slightly reduced corre-

Table 1a. Relationships of Carbon Uptakes With Surface Climate and TI for More Humid Years[a]

	Transmittance Index			Precipitation			Temperature		
	R^2	Slope	t-Test P-Value	R^2	Slope	t-Test P-Value	R^2	Slope	t-Test P-Value
NEP	0.66	−1178.0	0.02	0.01	−0.03	0.03	1.5e-3	−1.04	0.54
GEP	0.62	−1864.6	0.04	0.03	−0.08	0.04	6.e-4	−1.12	0.54
RESP	0.51	−686.64	0.08	0.07	−0.05	0.09	2E-05	−0.07	0.77

[a] Statistical analysis student's t-test is used to evaluate the significance of correlations. The confidence interval is 95% and $t_{0.05}$ = 2.776.

Table 1b. Same as the Table 1a but for Less Humid Years and $t_{0.05}$ = 2.571

	Transmittance Index			Precipitation			Temperature		
	R^2	Slope	t-Test P-Value	R^2	Slope	t-Test P-Value	R^2	Slope	t-Test P-Value
NEP	0.80	−884.94	1.7e-3	0.08	0.08	3.9e-3	0.02	−2.69	0.20
GEP	0.52	−878.97	0.02	2.6e-3	−0.02	1.9e-3	0.01	.1.75	0.23
RESP	2.e-4	5.97	0.66	0.52	−0.10	7.e-4	0.01	0.94	0.65

lations possibly related to changes of growing season duration.

[15] We have shown that clouds play a pivotal role in controlling carbon sequestration at a single midlatitude hardwood forest. Other studies have shown previously that in the past few decades terrestrial primary productivity has increased in the North American midlatitudes [*Keeling et al.*, 1996; *Myneni et al.*, 1997] and Amazonian rainforest [*Nemani et al.*, 2003]. However, in the same time period, observations have shown an increase in cloud cover over the North American midlatitudes [*IPCC*, 2001] but decreased cloud cover over tropical regions [*Chen et al.*, 2002; *Wielicki et al.*, 2002]. Studies have shown that reduced cloud cover enhances carbon sequestration in the tropical rainforest [*Graham et al.*, 2003].

[16] Our findings provide a mechanism which explains these observed trends of carbon exchanges, if we hypothesize that our results apply more generally. It is plausible that the characteristics of climate-ecosystem interaction in the North American midlatitudes are generally similar to that we observe at the Harvard Forest site: dominated by the cloud-enhanced carbon uptake regime. The Amazonian rainforest response may be dominated by the cloud-suppressed carbon uptake regime due to excessive cloud cover.

[17] **Acknowledgments.** The author thanks D. R. Fitzjarrald and S. Wofsy for their valuable comments and turbulent flux and radiation data. This research was supported by the Office of Science (BER), U.S. Department of Energy, through the Northeast Regional Center of the National Institute for Global Environmental Change (NIGEC) under Cooperative Agreement DE-FC03-90ER61010, through the Atmospheric Radiation Measurement (ARM) Grant DE-FG02-03ER63531, and by the NOAA Educational Partnership Program with Minority Serving Institutions (EPP/MSI) under cooperative agreements NA17AE1625 and NA17AE1623.

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