

Factors controlling CO₂ exchange in a middle latitude forest

Qilong Min¹ and Lingyun Wu^{1,2,3}

Received 2 December 2010; revised 27 July 2011; accepted 8 August 2011; published 2 November 2011.

[1] The forest carbon uptake experiences a relatively steady state, in which both radiation use efficiency and Bowen ratio exhibit relatively small change in tendency during the middle growing season at a deciduous forest in New England. The net ecosystem exchange (NEE) during the steady state varies from 2.1 to 5.1 Mg C Ha⁻¹ y⁻¹, accounting for 58–83% of the annual amount over 1992–2004. The cloudiness, combined with the effect of antecedent accumulated precipitation from late January, plays a key role in controlling interannual fluctuations of the steady state GEE and NEE among other environmental factors, and determines the long-term trend of the site GEE and NEE. These two factors account for 74% of the interannual variability of forest carbon uptake for the steady state, and 58% for the entire growing season, respectively. This suggests that winter precipitation and summer clouds probably play a key role in regulating the carbon uptake, an important mechanism of the carbon cycle/climate interaction.

Citation: Min, Q., and L. Wu (2011), Factors controlling CO₂ exchange in a middle latitude forest, *J. Geophys. Res.*, 116, D21301, doi:10.1029/2010JD015428.

1. Introduction

[2] The terrestrial ecosystem acts as a net carbon sink over the last two and one half decades, with a highly interannual variation, ranging from 0.3 to 5.0 PgCyr⁻¹ [Canadell *et al.*, 2007]. The interaction of climate with regional characteristics of ecosystems imposes complex controlling factors (e.g., temperature, precipitation, and radiation) on carbon uptake in different vegetation and climate regimes in the world [Braswell *et al.*, 1997; Churkina and Running, 1998; Nemani *et al.*, 2003; Barford *et al.*, 2001; Trenberth *et al.*, 2007]. Understanding climate factors that control interannual variability of the terrestrial ecosystem provides more confidence in the long term projections of human-induced global changes on the ecosystem. While hourly and daily variations of the terrestrial ecosystem are due to prompt ecosystem responses to ambient sunlight and temperature, monthly and seasonal anomalies reflect primarily weather and climate variations such as variations in cloudiness, deep snow in winter, drought in summer, El Niño, and volcanic eruption [Wofsy *et al.*, 1993; Fan *et al.*, 1995; Goulden *et al.*, 1996a; Barford *et al.*, 2001; Jones *et al.*, 2001; Nemani *et al.*, 2003; Gu *et al.*, 2003; Zeng, 2005; Dunn *et al.*, 2007; Min and Wang, 2008]. Although these studies suggest that multiple mechanisms control interannual carbon sequestration, the relative importance of environmental factors is not well understood in the context of ecosystem-climate-carbon

interaction [Urbanski *et al.*, 2007]. In particular, the role of clouds in this interaction requires further investigation, as recent research suggests clouds strongly mediate the interannual variability of both net ecosystem exchange and gross ecosystem exchange [Min and Wang, 2008].

[3] Here we analyze 1992–2007 turbulent exchange and radiation measurements at a northern hardwood forest (Harvard Forest, 42.5°N, 72.2°W), to quantify the relative importance of weather and climatic factors in determining interannual variations of radiation use efficiency (RUE) and gross ecosystem exchange (GEE) and net ecosystem exchange (NEE). Specifically, as clouds and precipitation are the consequences of atmosphere-vegetation interaction, we will investigate what is the most important factor controlling the photosynthesis process under clear sky conditions or the baseline RUE, and how clouds and associated precipitation enhance the RUE and modulate interannual variation of GEE and NEE.

2. Measurements and Method

[4] The Harvard Forest Environmental Monitoring Station (EMS) is located in north-central Massachusetts. The forest is 50–70 years old and contains a mixture of red oak, red maple, and hemlock, with an average tree height of 24 m. At Harvard Forest, turbulent fluxes of sensible and latent heat, momentum, and CO₂ are observed continuously from the 30 m level as well as at 11 m on a tower [Wofsy *et al.*, 1993] (<http://harvardforest.fas.harvard.edu/>). Upwelling and downwelling PAR, total shortwave radiation, and longwave radiation are measured by Atmospheric Sciences Research Center (ASRC) at State University of New York (SUNY) at Albany [Moore *et al.*, 1996].

[5] The net ecosystem exchange (NEE) is derived from the eddy correlation measurements of carbon uptake at the site with a procedure of flux screening and gap-filling. The

¹Atmospheric Sciences Research Center, State University of New York at Albany, Albany, New York, USA.

²State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, China.

³Center for Monsoon System Research, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China.

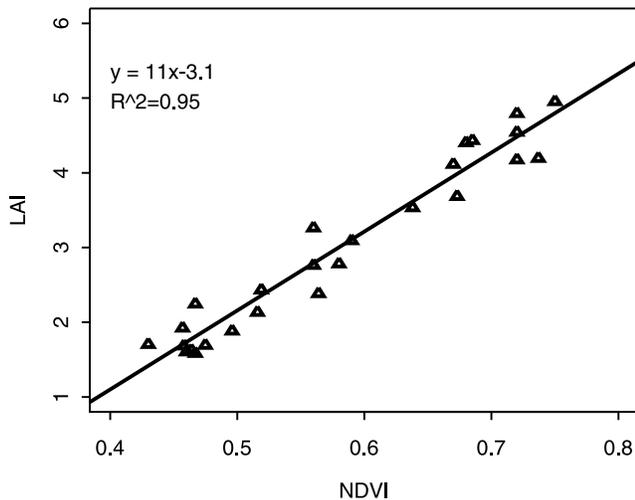


Figure 1. The relationship between leaf area index (LAI) and normalized difference vegetation index (NDVI).

gross ecosystem exchange (GEE) was calculated by subtracting respiration (RESP) from NEE, where respiration was measured directly at night and extrapolated for daytime on the basis of day-night changes in soil temperature. The meteorological data, including daily precipitation totals, snowfall, and minimum and maximum air temperature have been obtained from the Shaler and Fisher meteorological stations (<http://harvardforest.fas.harvard.edu/hfmet/>). More details on measurements and data processing are in the work of *Goulden et al.* [1996b] and *Urbanski et al.* [2007]. The long-term turbulent exchange and radiation measurements at Harvard Forest provide a unique opportunity to investigate the effects of aerosols and clouds on CO₂ uptake and water use efficiency [e.g., *Wofsy et al.*, 1993; *Goulden et al.*, 1996a; *Barford et al.*, 2001; *Urbanski et al.*, 2007; *Min and Wang*, 2008].

[6] Surface albedos at optical wavelengths directly link to the characteristics of surface properties, as a result of absorption and reflection of canopy. Studies showed that solar shortwave albedo and photosynthetically active radiation albedos are correlated with both the leaf area index (LAI) and the satellite-derived normalized difference vegetation index (NDVI) [*Moore et al.*, 1996]. To monitor physiological changes of the canopy, we used a new “normalized difference vegetation index” (“NDVI^T”) of observed photosynthetically active radiation (PAR) albedo and total shortwave albedo at the top of a flux tower:

$${}^{\text{T}}\text{NDVI} = (A_{\text{sw}} - A_{\text{PAR}})/(A_{\text{sw}} + A_{\text{PAR}}) \quad (1)$$

where A_{PAR} and A_{sw} are PAR and solar shortwave albedos, respectively. Since all radiation is observed at the top of a flux tower, this new “NDVI^T” provides a continued measure of canopy vegetation state even under cloudy conditions. LAI was obtained from the footprint of the EMS tower on Prospect Hill. Since LAI was measured throughout the entire growing season of 1998 and 1999, we chose the two years’ observations and corresponding daily “NDVI^T”s to compare. Figure 1 indicates that “NDVI^T” is closely linked to the leaf area index (LAI) with a correlation coefficient (R) of 0.98 for the two-year (1998 and 1999) observations at the site.

Combining in situ woody vegetation development observation [*O’Keefe*, 2005] and remote sensed “NDVI^T,” we are able to assess accurately seasonal variation of canopy leaf physiology and phenology.

[7] A fundamental variable affecting carbon uptake by ecosystems is the amount of photosynthetically active radiation (PAR)—not only the total amount, but also its spectral distribution, and its partitioning between direct and diffuse components [*Min*, 2005]. We use the atmospheric transmittance index (TI) as a measure of cloudiness and aerosol loading [*Min and Wang*, 2008]:

$$TI = \frac{I_t^{\text{obs}}}{\mu_0 I_0} = \sum_{i=1}^n (1 - C) T_{\text{clr}}(\tau_{\text{clr}}, wv) + C T_{\text{cld}}(\tau_{\text{cld}}, \tau_{\text{clr}}, wv) \quad (2)$$

where C is the cloud fraction, τ_{cld} , τ_{clr} , and wv are optical properties of cloud, aerosol, and water vapor, respectively. I_t^{obs} is the surface incoming solar radiation measured at the EMS tower. T_{clr} and T_{cld} are the transmittances of clear and cloudy sky, respectively. TI substantially reduces the dependency of solar radiation on solar zenith angle and solar distance by normalizing with $\mu_0 I_0$. Radiation impacts due to changes in aerosol and water vapor are relatively smaller than 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. 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.

3. Results

3.1. Growing Season and Its Steady State Period

[8] Accurate assessments of leaf physiology and phenology are crucial for the estimations of CO₂ uptake by the ecosystem in the global carbon cycle [*Schwartz*, 1999; *Cayan et al.*, 2001; *Lucht et al.*, 2002; *Nemani et al.*, 2003]. Through its influence on the radiation fields of forest canopies and the restriction of momentum exchange of atmosphere and surface, the seasonally changing leaf physiology of the canopy has a dramatic impact not only on the land-atmosphere exchange of moisture and CO₂ uptake fluxes, but also on sub-canopy exchange processes. As discussed in the previous section, seasonal variation of canopy leaf physiology and phenology can be assessed accurately by the remote sensed “NDVI^T” from the flux tower.

[9] Using the year 1993 as an example (Figure 2a), “NDVI^T” indicates that the starting dates of leaf emergence and senescence were at about 120 and 293 Julian days, which correspond well with surface observed initial bud break and leaf fall [*O’Keefe*, 2005]. Figure 2a also includes variations of radiation use efficiency (RUE) and Bowen ratio (BR), representing changes in carbon uptake and evapotranspiration processes. Obviously “NDVI^T,” RUE, and BR changed dramatically after leaves emerged, reached their own relatively steady state in the middle of the growing season, and then changed during leaf senescence. RUE increased slowly to reach a relative equilibrium value when the leaves were fully expanded and developed at about 21 days after the “NDVI^T” reached its steady state. After about 83 days in the relatively steady state, RUE started to decrease about 24 days before “NDVI^T” appeared to

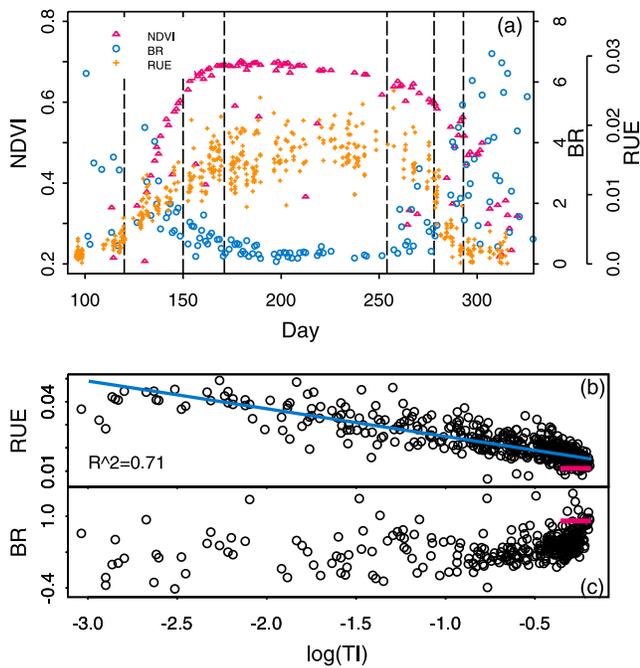


Figure 2. (a) Time series of NDVI, radiation use efficiency (RUE), and Bowen ratio (BR). The vertical lines denote the transitions of NDVI and BE in spring and fall, respectively. (b) Relationships between daily transmittance index (TI) and radiation use efficiencies (RUE) and (c) Bowen ratio (BR) in summer 1993. The horizontal lines denote the baseline of RUE and BR under clear sky condition, respectively.

decline. Physiologic changes of the canopy indicated by the decline of “NDVI^T” accelerated the decrease of RUE. BR exhibited a consistent seasonal evolution and steady state period with RUE.

[10] The timing of an abrupt change in various phenological, physiological, and meteorological parameters with different tendencies represents the state change of corresponding parameters. The steady state we defined is the

period in which the parameter exhibits relatively small change in tendency, as discussed previously and illustrated in Figure 2a. Using the statistic package of Kolmogorov-Zurbenko adaptive algorithm for image detection (KZA), R-software, we estimate key phenological times and other physiological and meteorological parameters in each year from 1992 to 2004. As listed in Table 1, the beginning dates of “NDVI^T” steady states are different from that of RUE every year because physiological processes associated with leaves have an annual cycle shorter than that of their physical presence [Sakai *et al.*, 1997]. The lagged days are strongly correlated with the precipitation during the periods, with a correlation coefficient of 0.88 (Figure 3a). Since the observed “NDVI^T” represents LAI or vegetation state of the canopy, water supply, through precipitation after the “NDVI^T” (or LAI) reaches its maximum, further thickens leaves and develops subcanopy vegetation. Such a process substantially enhances the canopy photosynthesis capability and does not change “NDVI^T,” resulting in the lagged days between the starting dates. In fall the steady state of RUE also ends on the different dates from that of “NDVI^T,” and the led days are also correlated with the precipitation during the periods ($R = 0.75$, Figure 3b). It indicates water availability during the fall transition period plays a key role in prolonging the growing season. Furthermore, the length of the steady state of photosynthesis is inversely proportional to the antecedent accumulated precipitation (AAP, more discussion later) with a correlation coefficient of 0.23 (Figure 3c). As mentioned previously, precipitation in spring will enlarge lag time between the beginning dates of “NDVI^T” and RUE, thus decreasing the length of RUE steady state. The more AAP, the shorter BR or RUE steady state length.

[11] In general, the lag times between the beginning dates of NDVI^T and RUE steady states, and the time differences between the ending dates of steady state of RUE and NDVI^T are strong correlated with the precipitation during these periods. The forest sequesters 2.6–5.5 Mg C Ha⁻¹ y⁻¹ carbon during a growing season, in which about 2.1–5.1 Mg C Ha⁻¹ y⁻¹ occurs during the steady state period of RUE and

Table 1. The Beginning Dates and Ending Dates of Leaves, Normalized Difference Vegetation Index, and Bowen Ratio

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Emergency of leaves	133	120	127	135	120	135	120	126	129	123	122	134	128	131	128	129
Sencence of leaves	289	293	311	309	303	299	304	314	302	317	305	295	316	315	311	315
Beginning date of NDVI steady state	160	150	158	155	150	161	141	149	150	149	151	161	145	145	153	151
Ending date of NDVI steady state	279	278	278	277	272	275	279	273	286	279	261	280	289	294	275	282
Beginning date of RUE steady state	175	171	170	162	164	169	176	155	169	171	174	176	160	160	166	168
Ending date of RUE steady state	264	254	260	266	259	266	256	265	268	259	241	248	276	268	252	271
Length of growing season	156	173	184	174	183	164	184	188	173	194	183	161	188	184	183	186
Length of NDVI steady state	119	128	123	122	122	114	138	124	136	130	110	119	144	149	122	131
Length of BR steady state	89	83	90	104	95	97	80	110	99	88	67	72	116	108	86	103
Lag time of beginning of NDVI and RUE	15	21	12	7	14	8	35	6	19	22	23	15	15	15	13	17
Lag time of ending of NDVI and RUE	15	24	18	11	13	9	23	8	18	20	20	32	13	26	23	11
Sum of precipitation in RUE-NDVI spring	44.2	63.3	16.1	3.1	85.9	27.4	199.1	0	107.6	103.8	97	54.8	50	80.2	59.8	47.3
Sum of precipitation in RUE-NDVI fall	33.6	107.3	99.7	11.7	117.1	10.2	34.3	0	34.3	78.5	31	125.5	4.2	266.3	90.4	7.5

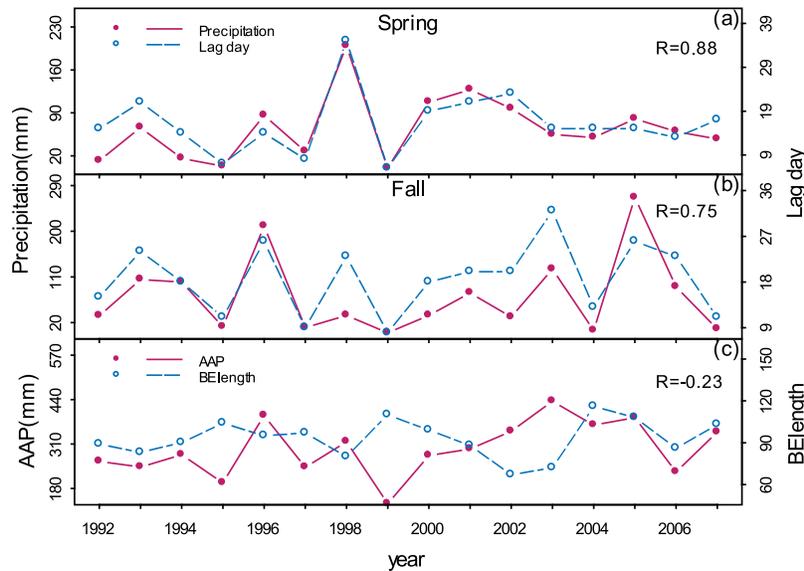


Figure 3. Time series of lagged/led time length and precipitation over the transition period in (a) spring and (b) fall, and (c) AAP and length of steady state.

BE. Carbon uptake during the steady state period represents about 58–83% of the total amount during the entire growing season. Understanding controlling factors on carbon uptake during the steady state period will provide insights on regulation of the interannual fluctuations of photosynthesis during the growing season.

[12] RUE maintains a relatively constant value under clear sky during the steady state of the growing season and gradually increases with increasing cloud cover (decreasing TI), shown in Figure 2b for year 1993 ($R^2 = 0.71$). Similarly, BR exhibits a decreasing trend with the increase of cloud cover (Figure 2c). All years from 1992 through 2007 have the same pattern. The result implies that there are different carbon uptake mechanisms under clear sky and cloudy conditions; thereby, we explore the response of RUE to TI by separating clear sky and cloudy sky.

3.2. Photosynthesis Under Clear Sky Conditions in Steady State

[13] RUE increased with increasing cloud cover under cloudy sky, but it kept a relatively constant minimum value under clear sky (TI greater than 0.7), as shown in Figure 2b. We used the averaged RUE of 20 minimum values under the clear sky conditions to represent the baseline photosynthesis capability of the forest. Similarly, BR maintained a relatively maximum value under the clear sky, which indicated potential energy balance during the steady state of the year. We used the averaged BR of 20 maximum values under the clear sky conditions to represent the baseline potential energy balance. The baseline RUE and BR varied from 0.0084 to 0.0163 and 0.87 to 2.11 from 1992 to 2007, respectively. The interannual variabilities of both baselines were closely linked to AAP, and Figure 4 exhibits correlations of clear sky radiation use efficiency (RUE) and Bowen ratio (BR) over the RUE steady state with AAP over the different periods. It is clear that the accumulated precipitation from 80 to 110 days before RUE reached its steady state; i.e., precipitation and

snowfall in late January to late March, plays a vital role in regulating the baseline RUE under clear sky conditions in the mid-summer steady state. The more AAP, the higher the baseline RUE is. The correlation coefficient between the baseline RUE and AAP reaches its maximum of 0.70 (above 99% confidence level) at 90 day accumulation. BR during the steady state showed a much weaker correlation with AAP, and it reached its maximum of 0.53 (above 95% confidence level) at 120 day accumulation.

[14] In winter temperatures are cold and the evaporation process is slow. Water from precipitation during winter can be stored in the deeper soil or a snowpack for resupplying water in soil later, ensuring the provision of water resources for the upcoming summer [Knapp *et al.*, 2002; Saigusa *et al.*, 2005; Fung *et al.*, 2005]. Trees in the forest with deeper roots in the depth of soil, where soil moisture memory

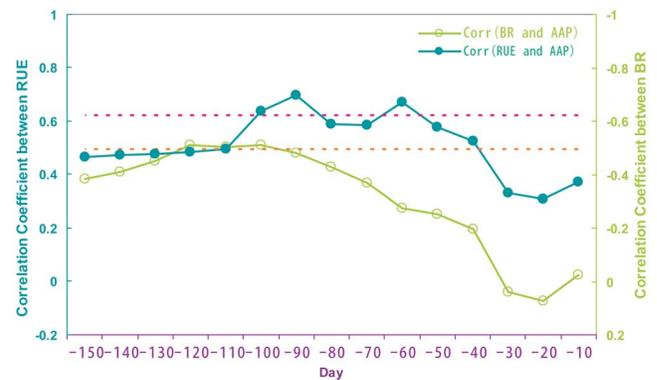


Figure 4. Correlations of clear sky radiation use efficiency (RUE) and Bowen ratio (BR) over the equilibrium period with antecedent accumulated precipitation (AAP) over the different periods. Yellow and pink dashed lines denote 95 and 99% confidence levels, respectively.

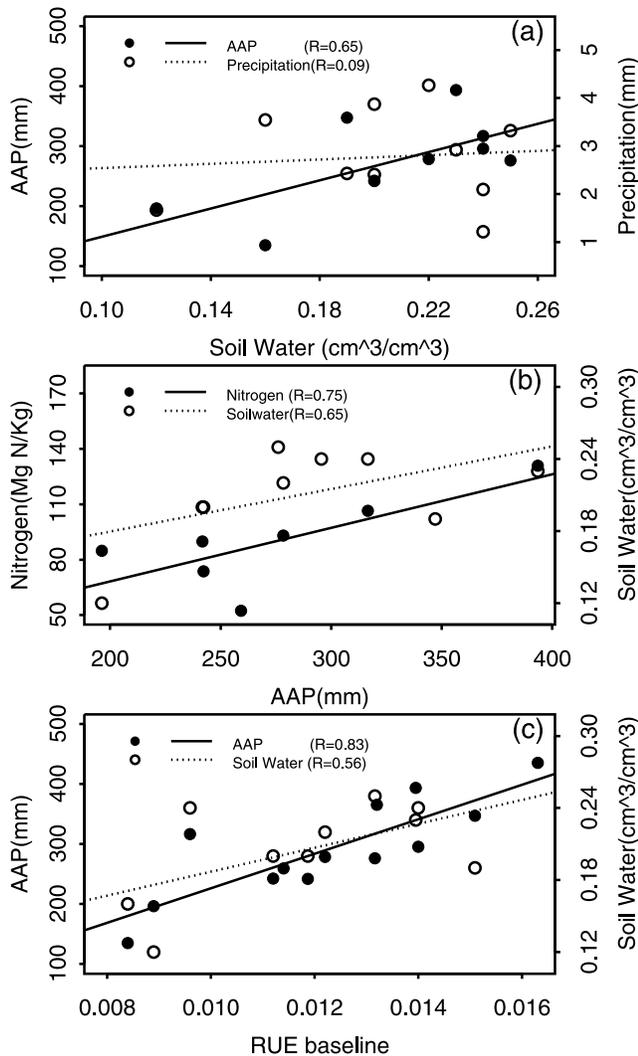


Figure 5. Scatterplots of (a) AAP and precipitation as functions of soil water (1993–2002), (b) nitrogen (1992–1998) and soil water as functions of accumulated precipitation for the steady stage, and (c) AAP and soil water as functions of RUE baseline.

is long, enable them to uptake the water stored a long time ago. The correlation coefficient of observed averaged soil moisture at a depth of 50 cm during the steady state with AAP is 0.65 ($p < 0.044$, LS > 95%) and is much better than with precipitation during the steady state (Figure 5a), further illustrating the importance of AAP on regulating soil moisture. Furthermore, deep snowpack insulates the soil to maintain soil temperature and allows microbes to remain active and release nitrogen [Grogan and Jonasson, 2003]. The conditions during winter control soil nutrient availability not only during thaw, but throughout the growing season as well [Schimel et al., 2004]. As shown in Figure 5b, the correlation coefficient between AAP and measured nitrogen during the steady state from 1992 to 1998 is 0.75. The photosynthesis rate increases with increasing amount of nitrogen in foliage. Therefore, combined effects of AAP on soil moisture and nitrogen determine the baseline RUE, and

thus photosynthesis process during the steady state under clear sky conditions.

[15] As shown in Figure 6a, the correlation coefficient between AAP and the baseline RUE is about 0.70. Year 1998 is a special El Nino year with disturbance events occurring at Harvard Forest: The scant snow cover with a widespread ice storm in 1998; a warm spring with early commencement in mid May and followed by a frost event with a minimum temperature of -2°C ; and severe thunderstorms passed through the area on 30–31 May [e.g., Urbanski et al., 2007]. Those disturbance events might damage the foliage or retard canopy development and decrease canopy photosynthetic capacity [Urbanski et al., 2007]. Excluding year 1998, the overall correlation coefficient between AAP and the baseline RUE improves to 0.77. It is worth noting that although soil moisture may play a key role in regulating the baseline RUE, AAP has better correlation with the baseline RUE than soil moisture (Figure 5c).

3.3. Photosynthesis Under Cloudy Conditions in Steady State

[16] Clouds can enhance the radiation use efficiency [Min, 2005] by (1) enhancing diffuse radiation that can penetrate deeper into the canopy and have a favorable spectral distribution for photosynthesis [Hollinger et al., 1994; Gu et al., 1999; Fan et al., 1995]; and (2) increasing relative humidity and reduce leaf temperature in the forest, thus decreasing water vapor pressure deficit and stimulate carbon uptake [Freedman et al., 2001; Min and Wang, 2008]. Carbon uptake in an ecosystem is influenced by multiple variables, some of them are usually correlating each other. In their auxiliary material (<http://www.agu.org/journals/gl/gl0802/2007GL032398/>), Min and Wang [2008] have investigated relationship and co-variance among environmental factors using both multiregression analysis and principal component analysis, and demonstrated that clouds are the dominate factor among all variables. Clouds not only promptly affect instant carbon uptake as a major factor to control sunlight reaching forest canopy, but also may play a pivotal role in driving the interannual variability of terrestrial carbon uptake by forest and are an important mechanism of the carbon cycle/climate interaction [Min and Wang, 2008].

[17] As shown in Figure 2b, the RUE increases quasi-linearly with cloudiness. The slope of the least squares fits for RUE and TI presents the canopy photosynthesis response to the presence of clouds, apparently exhibiting interannual variability (Figure 6b). Interannual variability of canopy response to clouds is strongly associated with the vegetation state or leaf development, i.e., “NDVI^T.” Except for 1998 and 2003, years with better leaf development, i.e., higher “NDVI^T,” have stronger responses (larger slopes) to clouds.

[18] Min and Wang [2008] demonstrated that the tradeoff 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. There is a positive relationship between carbon sequestration and cloudiness when cloud variability varies within the cloud enhanced carbon uptake regime. The reverse is true in the cloud suppressed carbon uptake regime. The cloud distribution, a consequence of atmosphere-vegetation interaction, during a growing season or in the steady state, is crucial in determining

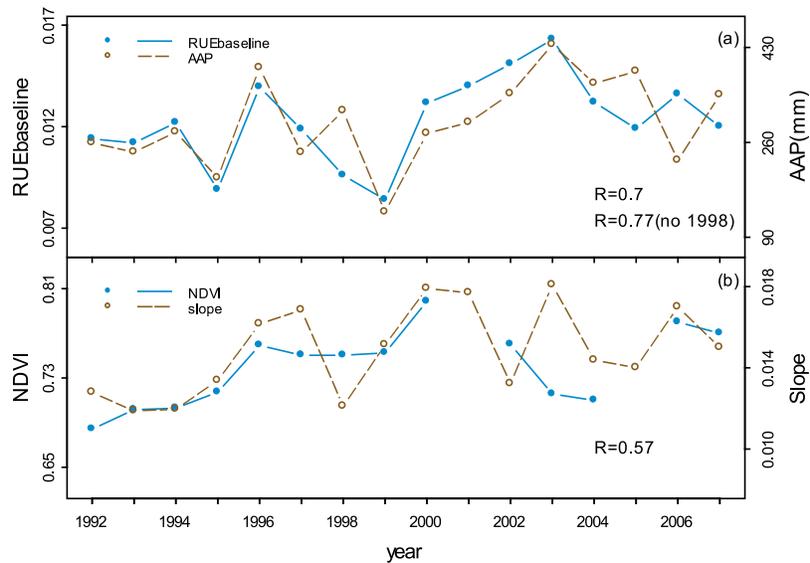


Figure 6. Time series of (a) AAP and RUE baselines and (b) NDVI and slopes of regression of RUE and TI.

photosynthesis during the period. We use first two moments of TI distribution, mean and standard deviation, to represent the cloud distribution. Since clouds are quasi-independent of AAP (not shown), we use clouds and the AAP as fundamental factors to understand the interannual variability of photosynthesis during the steady state.

[19] First, the averaged GEE during the steady state is strongly correlated with two factors, shown in Figure 7c, with a correlation coefficient of 0.71. Excluding the abnormal year of 1998, the correlation coefficient improves significantly to 0.86. Furthermore, without year 1998, clouds and AAP contribute about 58 and 21% to variability ($R1 = 0.76$ and 0.45 in Figures 7a and 7b), respectively. It suggests that in normal years clouds possibly play a pivotal role in regulating interannual variability of carbon uptake [Min and Wang, 2008]. Since AAP is associated with the baseline of photosynthesis capacity, AAP may also play a key role in regulating the interannual variability of carbon uptake. In the El Niño year of 1998, however, some other factors beyond these two fundamental factors may have some impact on the photosynthesis process in the year [Urbanski *et al.*, 2007].

[20] Both averaged NEE and RESP exhibit similar correlation patterns with two key factors: clouds and AAP, shown in Figures 7d and 7e and listed in Table 2. The correlation coefficients of GEE, NEE, and RESP with the two factors are 0.86 and 0.73, respectively. In Table 2, we also list the correlation coefficients of GEE, NEE, and RESP with other factors such as averaged temperature and precipitation during the steady state periods. Statistics suggest that clouds and AAP are two critical factors in deriving the interannual variability of carbon sequestration processes. The variability of averaged NEE can be explained more by the cloud factor than by the AAP factor. However, the reverse is true for the averaged RESP, as AAP is more directly linked to the soil moisture. Although heat is a prerequisite for biochemical reactions, temperature does not affect photo-

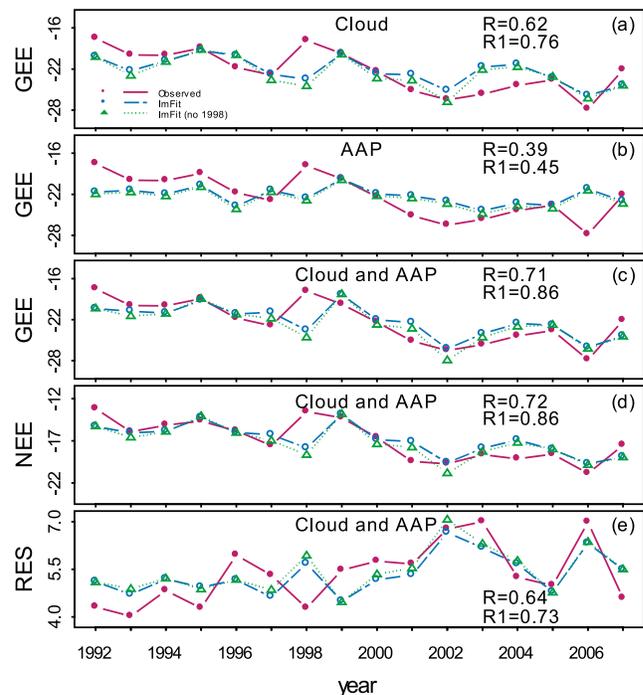


Figure 7. The observed and predicted average GEE during steady state at the Harvard Forest EMS using: (a) cloud and AAP factors, (b) cloud factor, and (c) AAP factor. The solid line indicates the observed annual average GEE, the long dashed line indicates the average GEE predicted from 1992 to 2007, the short dashed line indicates the predicted average GEE without 1998; (d), for NEE, and (e) for RESP. R is the correlation coefficient of observed and predicted GEE, NEE, and RESP ($1000 \mu\text{mol m}^{-2} \text{S}^{-1}$), and R1 represents the correlation coefficient of observed and predicted GEE, NEE, and RESP without 1998.

Table 2. Correlation and p-value Between CO₂ Exchange and Weather and Climatic Factors During Steady State and Growing Season^a

	NEE (R, P)		GEE (R, P)		RES (R, P)	
	Mean	Total	Mean	Total	Mean	Total
Cloud						
Steady state	0.62 ^b , 0.02 (0.76 ^b , 0.00)	0.74 ^b , 0.01	0.62 ^b , 0.04 (0.76 ^b , 0.01)	0.70 ^b , 0.01	0.59 ^c , 0.33 (0.73 ^b , 0.16)	0.91 ^b , 0.00
Growing season	0.64 ^b , 0.03 (0.65 ^b , 0.04)	0.59 ^c , 0.07	0.42, 0.28 (0.39, 0.36)	0.41, 0.29	0.23, 0.69 (0.25, 0.68)	0.42, 0.28
AAP						
Steady state	0.39, 0.13 (0.45 ^c , 0.09)	0.53 ^d , 0.03	0.39, 0.13 (0.45 ^c , 0.09)	0.31, 0.24	0.39, 0.26 (0.45 ^c , 0.22)	0.13, 0.64
Growing season	0.40, 0.13 (0.51 ^d , 0.05)	0.40, 0.12	0.4, 0.13 (0.51 ^d , 0.05)	0.37, 0.15	0.14, 0.61 (0.16, 0.56)	0.13, 0.63
Cloud and AAP						
Steady state	0.72 ^b , 0.07 (0.86 ^b , 0.00)	0.77 ^b , 0.01	0.71 ^b , 0.08 (0.86 ^b , 0.01)	0.75 ^b , 0.02	0.64 ^b , 0.17 (0.73 ^b , 0.08)	0.91 ^b , 0.00
Growing season	0.70 ^b , 0.04 (0.75 ^b , 0.02)	0.64 ^b , 0.09	0.55 ^d , 0.13 (0.73 ^b , 0.14)	0.49 ^c , 0.33	0.32, 0.72 (0.35, 0.68)	0.44, 0.44
Temperature						
Steady state	-0.16, 0.57 (-0.23, 0.43)		0.11, 0.7 (0.11, 0.7)		0.37, 0.18 (0.40, 0.16)	
Growing season	-0.04, 0.89 (-0.10, 0.72)		0.37, 0.18 (0.37, 0.19)		-0.31, 0.26 (-0.30, 0.30)	
Precipitation						
Steady state	-0.08, 0.78 (0.19, 0.51)		0.17, 0.52 (0.19, 0.56)		-0.06, 0.04 (-0.18, 0.52)	
Growing season	-0.42, 0.11 (-0.31, 0.26)		0.51 ^d , 0.04 (0.52 ^d , 0.05)		-0.22, 0.42 (-0.29, 0.29)	

^aCorrelation, R; p-value, P; CO₂ exchange, NEE, GEE, and RESP. Mean represents the averaged NEE, GEE, and RESP, and sum is the sum of NEE, GEE, and RESP. The results without 1998 are shown in parentheses.

^bCorrelation coefficients are statistically significant level at the 99% level.

^cCorrelation coefficients are statistically significant level at the 98% level.

^dCorrelation coefficients are statistically significant level at the 95% level.

^eCorrelation coefficients are statistically significant level at the 90% level.

synthesis excessively. Photosynthesis is restricted to a certain temperature range, within which it influences less on the interannual variability of carbon uptake [Min and Wang, 2008]. Precipitation increases or maintains the soil moisture and reduces water stress on the ecosystem [Nemani et al., 2003]. As the baseline RUE and soil water may be regulated by AAP, precipitation during the steady state exerts mild impacts on the interannual variability of carbon uptake. It is worth noting that the total GEE, NEE, and RESP during the steady state, even including 1998, can be fitted very well by cloudiness, AAP, and the length of steady state, R = 0.75, R = 0.77, and R = 0.91, respectively, shown in Figure 8 (and Table 2). More importantly, as shown in Figures 7 and 8, the long-term trends in GEE, NEE, and RESP can be simply explained by the long-term trend in both cloud and AAP factors. Fundamentally, the increase trend of AAP (Figure 6a) determines the increase trend of the baseline RUE, resulting in the basic increase trends in GEE and NEE. Furthermore, the increase trend of cloudiness, shown in Figures 7a and 8a, amplifies the increase trends of GEE (and NEE). Therefore, clouds and AAP play vital roles not only in regulating the interannual variability of carbon exchange but also in determining the long-term trend in annual carbon exchange.

3.4. Photosynthesis in Transition Periods and During the Growing Season

[21] Transition periods in both spring and fall contribute a small but significant portion of seasonal carbon uptake.

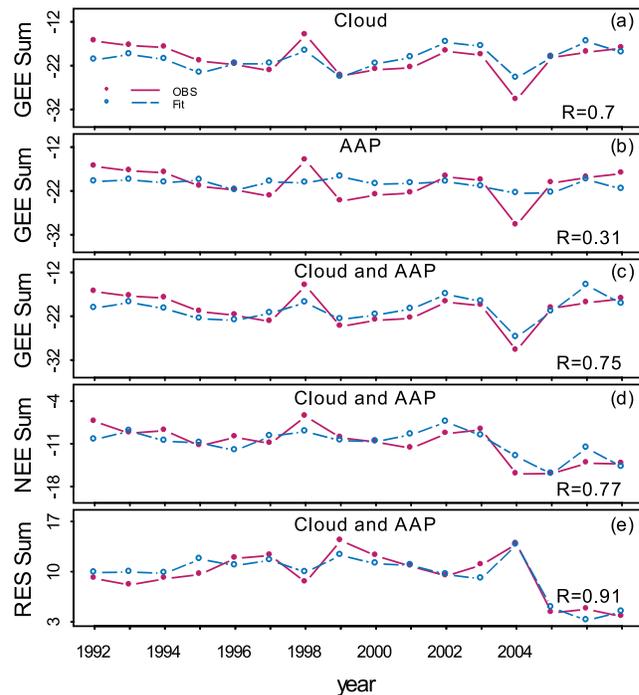


Figure 8. The same as Figure 7, but for the total GEE during steady state at the Harvard Forest EMS.

Temperature in early spring controls nearly all physiological processes of plant growth and the rate of chemical reactions, as they are initiated in specific temperature regimes. Thus carbon uptake in spring is closely linked to prompt temperature with a correlation coefficient of 0.52. In fall, as the rate of photosynthesis decreases because a leaf becomes desiccated and its foliage water potential decreases, soil water is essential. Hence, precipitation and cloudiness during the fall transition possibly lengthen the growing season and enhance the carbon uptake. Overall for the entire growing season, as listed in Table 2, cloudiness and AAP again may play controlling roles in regulating the interannual fluctuations of photosynthesis in the growing season. The correlation coefficients of averaged NEE, GEE, and RESP with the two factors are 0.77, 0.75, and 0.91, respectively. Similarly the total GEE, NEE, and RES during the growing season, even including 1998, can be fitted well by cloudiness, AAP, and the length of growing season, $R = 0.64$, $R = 0.49$, and $R = 0.44$, respectively (Table 2). These coefficients are slightly worse than those during the steady state, as temperature in early spring and precipitation in the fall also play some roles.

4. Conclusions and Discussion

[22] Our ability to predict future changes of carbon cycle is contingent upon how well we can identify and understand the relative importance of environmental factors in controlling the terrestrial ecosystem. The analysis of 16 year measurements at a midlatitude deciduous forest showed that physiological processes associated with leaves have an annual cycle shorter than that of their physical presence. Also, NEE experienced a relatively steady state in the middle growing season, which accounted for most of the annual amount. Antecedent accumulated precipitation from late January to late March may be the most important factor controlling the baselines of RUE and BR under clear sky conditions, because it possibly regulates soil moisture and nitrogen that supply water and nutrition for photosynthesis. The cloud distribution during a growing season or in a steady state, a consequence of atmosphere-vegetation interaction, is crucial in determining photosynthesis during the period, as clouds enhance the radiation use efficiency (RUE) through enhancing diffuse radiation with better angular and spectral distributions and decreasing water vapor pressure deficit with higher relative humidity and lower leaf temperature. Although temperature in early spring and precipitation in the fall influence carbon uptake for the entire growing season, clouds and AAP may still play vital roles in regulating the interannual variations of carbon exchange. Other factors, however, have limited effects on the interannual variability of carbon exchange. More importantly, clouds and AAP play vital roles not only in regulating the interannual variability of carbon exchange but also in determining the long-term trend in annual carbon exchange.

[23] Seasonal and annual climate variability is often coherent over large spatial and long temporal scales. If the characteristic of climate-ecosystem interaction at Harvard Forest is typical of northern American forests, the two climate factors, cloud cover and antecedent accumulated precipitation, will probably play a key role in regulating the carbon uptake of the northern terrestrial biosphere. It sug-

gests a new mechanism of carbon cycle/climate interaction. How the global ecosystem responds to the described mechanism of carbon cycle/climate interaction remains to be evaluated.

[24] **Acknowledgments.** We thank D. R. Fitzjarrald, and S. Wofsy for their valuable comments and turbulent flux and radiation data. We also thank I. Zurbenko for recommending R-KZA software. 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.

References

- Barford, C. C., et al. (2001), Factors controlling long- and short-term sequestration of atmospheric CO₂ in a mid-latitude Forest, *Science*, 294, 1688–1691, doi:10.1126/science.1062962.
- Braswell, B. H., D. S. Schimel, E. Linder, and B. Moore III (1997), The response of global terrestrial ecosystems to interannual temperature variability, *Science*, 278, 870–873, doi:10.1126/science.278.5339.870.
- Canadell, J. G., D. E. Pataki, R. Gifford, R. A. Houghton, Y. Luo, M. R. Raupach, P. Smith, and W. Steffen (2007), Saturation of the terrestrial carbon sink, in *Terrestrial Ecosystems in a Changing World*, *IGBP Ser.*, edited by J. G. Canadell, D. E. Pataki, and L. F. Pitelka, chap. 6, pp. 59–78, Springer, Berlin, doi:10.1007/978-3-540-32730-1.
- Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson (2001), Changes in the onset of spring in the western United States, *Bull. Am. Meteorol. Soc.*, 82, 399–415, doi:10.1175/1520-0477(2001)082<0399:CITOO>2.3.CO;2.
- Churkina, G., and S. W. Running (1998), Contrasting climatic controls on the estimated productivity of different biomes, *Ecosystems*, 1, 206–215, doi:10.1007/s100219900016.
- Dunn, A. L., C. C. Barford, S. C. Wofsy, M. L. Goulden, and B. C. Daube (2007), A long-term record of carbon exchange in a boreal black spruce forest: Means, responses to interannual variability, and decadal trends, *Global Change Biol.*, 13, 577–590, doi:10.1111/j.1365-2486.2006.01221.x.
- Fan, S.-M., M. L. Goulden, J. W. Munger, B. C. Daube, P. S. Bakwin, S. C. Wofsy, J. S. Amthor, D. R. Fitzjarrald, K. E. Moore, and T. R. Moore (1995), Environmental controls on the photosynthesis and respiration of a boreal lichen woodland: A growing season of whole-ecosystem exchange measurements by eddy correlation, *Oecologia*, 102, 443–452, doi:10.1007/BF00341356.
- Freedman, J. M., et al. (2001), Boundary layer clouds and vegetation-atmosphere feedbacks, *J. Clim.*, 14, 180–197, doi:10.1175/1520-0442(2001)013<0180:BLCAVA>2.0.CO;2.
- Fung, I., S. C. Doney, K. Lindsay, and J. John (2005), Evolution of carbon sinks in a changing climate, *Proc. Natl. Acad. Sci. U. S. A.*, 102, 11,201–11,206, doi:10.1073/pnas.0504949102.
- Goulden, M. L., J. W. Munger, S. M. Fan, B. C. Daube, and S. C. Wofsy (1996a), Effects of interannual climate variability on the carbon dioxide exchange of a temperate deciduous forest, *Science*, 271, 1576–1578, doi:10.1126/science.271.5255.1576.
- Goulden, M. L., J. W. Munger, S.-M. Fan, B. C. Daube, and S. C. Wofsy (1996b), Measurements of carbon storage by long-term eddy correlation: Methods and a critical evaluation of accuracy, *Global Change Biol.*, 2, 169–182, doi:10.1111/j.1365-2486.1996.tb00070.x.
- Grogan, P., and S. Jonasson (2003), Controls on annual nitrogen cycling in the understory of a subarctic birch forest, *Ecology*, 84(1), 202–218, doi:10.1890/0012-9658(2003)084[0202:COANCI]2.0.CO;2.
- Gu, L., J. D. Fuentes, H. H. Shugart, R. M. Staebler, and T. A. Black (1999), Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: Results from two north American deciduous forests, *J. Geophys. Res.*, 104, 31,421–31,434, doi:10.1029/1999JD901068.
- Gu, L., et al. (2003), Response of a deciduous forest to the Mount Pinatubo eruption: Enhanced photosynthesis, *Science*, 299, 2035–2038, doi:10.1126/science.1078366.
- Hollinger, D. Y., F. M. Kelliher, J. N. Byers, J. E. Hunt, T. M. McSeveny, and P. L. Weir (1994), Carbon dioxide exchange between an undisturbed old-growth temperate forest and the atmosphere, *Ecology*, 75, 134–150, doi:10.2307/1939390.
- Jones, C. D., M. Collins, P. M. Cox, and S. A. Spall (2001), The carbon cycle response to ENSO: A coupled climate-carbon cycle model study,

- J. Clim.*, 14, 4113–4129, doi:10.1175/1520-0442(2001)014<4113:TCCRTE>2.0.CO;2.
- Knapp, A. K., et al. (2002), Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland, *Science*, 298, 2202–2205, doi:10.1126/science.1076347.
- Lucht, W., et al. (2002), Climatic control of the high-latitude vegetation greening trend and Pinatubo effect, *Science*, 296, 1687–1689, doi:10.1126/science.1071828.
- Min, Q. (2005), Impacts of aerosols and clouds on CO₂ uptake over Harvard Forest, *J. Geophys. Res.*, 110, D06203, doi:10.1029/2004JD004858.
- Min, Q., and S. Y. Wang (2008), Clouds modulate terrestrial carbon uptake in a mid-latitude hardwood forest, *Geophys. Res. Lett.*, 35, L02406, doi:10.1029/2007GL032398.
- Moore, K. E., D. R. Fitzjarrald, R. K. Sakai, M. L. Goulden, J. W. Munger, and S. C. Wofsy (1996), Seasonal variations in radiative and turbulent exchange at a deciduous forest in central Massachusetts, *J. Appl. Meteorol.*, 35, 122–134, doi:10.1175/1520-0450(1996)035<0122:SVIRAT>2.0.CO;2.
- Nemani, R. R., et al. (2003), Climate-driven increases in global terrestrial net primary production from 1982 to 1999, *Science*, 300, 1560–1563, doi:10.1126/science.1082750.
- O’Keefe, J. (2005), *Woody Species Phenology, Prospect Hill Tract, Harvard Forest-2004: Proceedings of Harvard University LTER and NIGEC Programs*, Harvard Forest, Harvard Univ., Cambridge, Mass.
- Saigusa, N., S. Yamamoto, S. Murayama, and H. Kondo (2005), Interannual variability of carbon budget components in an AsiaFlux forest site estimated by long-term flux measurements, *Agric. For. Meteorol.*, 134, 4–16, doi:10.1016/j.agrformet.2005.08.016.
- Sakai, R. K., D. R. Fitzjarrald, and K. E. Moore (1997), Detecting leaf area and surface resistance during transition seasons, *Agric. For. Meteorol.*, 84, 273–284, doi:10.1016/S0168-1923(96)02359-3.
- Schimel, J. P., C. Bilbrough, and J. M. Welker (2004), Increased snow depth affects microbial activity and nitrogen mineralization in two Arctic tundra communities, *Soil Biol. Biochem.*, 36(2), 217–227, doi:10.1016/j.soilbio.2003.09.008.
- Schwartz, M. D. (1999), Advancing to full bloom: Planning phenological research for the 21st century, *Int. J. Biometeorol.*, 42, 113–118, doi:10.1007/s004840050093.
- Trenberth, K. E., P. Ambenje, R. Bojariu, D. Easterling, A. Klein Tank, D. Parker, F. Rahimzadeh, J. A. Renwick, M. Rusticucci, B. Soden, and P. Zhai (2007), Observations: Surface and atmospheric climate change, in *Climate Change 2007: The Physical Science: Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. D. Solomon et al., pp. 235–249, Cambridge Univ. Press, New York.
- Urbanski, S., et al. (2007), Factors controlling CO₂ exchange on timescales from hourly to decadal at Harvard Forest, *J. Geophys. Res.*, 112, G02020, doi:10.1029/2006JG000293.
- Wofsy, S. C., et al. (1993), Net exchange of CO₂ in a midlatitude forest, *Science*, 260, 1314–1317, doi:10.1126/science.260.5112.1314.
- Zeng, N. (2005), Terrestrial mechanisms of interannual CO₂ variability, *Global Biogeochem. Cycles*, 19, GB1016, doi:10.1029/2004GB002273.

Q. Min, Atmospheric Sciences Research Center, State University of New York at Albany, Albany, NY 12203, USA. (min@asrc.albany.edu)
 L. Wu, State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China.