Impacts of aerosols and clouds on forest-atmosphere carbon exchange

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[1] The impact of aerosols and clouds on CO_2 uptake and water use efficiency at Harvard Forest has been studied by using collocated turbulent flux and radiation measurements. Measurements of a multifilter narrowband radiometer provide both direct and diffuse components of photosynthetically active radiation (PAR) by product integrals of synthesized spectra, with a normalized action spectrum for canopy photosynthesis. Optical properties of aerosols and clouds are also retrieved from the radiometer data. Optical properties of aerosols and clouds have significant impacts on photosynthesis not only through changes of the total amount of PAR but also through changes of its spectral distribution (or light quality) and its partitioning between direct and diffuse components. The diffuse PAR is much greater under patchy/thin cloud conditions than under aerosol conditions for a given optical depth. The "diffuse radiation use efficiency" coefficients are 3.40 and 1.95 for patchy/thin clouds and aerosols, respectively. Furthermore, the radiation use efficiency of CO_2 uptake under clouds which completely block direct beam solar (optically thick clouds) is approximately 57 and 13% higher than under aerosol and patchy/thin clouds, respectively. The water use efficiency also showed significant enhancement as atmospheric conditions changed from aerosols, to patchy/thin clouds, and then to clouds opaque to direct solar radiation. Under optically thick cloud conditions the water use efficiency is almost 5 and 3 times greater than under aerosol and patchy/thin cloud conditions, respectively. These indicate that an increase of diffuse radiation may not be the only factor responsible for the enhancement of carbon assimilation under cloudy conditions. Changes in many other factors, such as temperature, moisture, latent heating, and precipitation, in the presence of clouds may have both direct and indirect influences on carbon assimilation.

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1. Introduction

[2] Photosynthetically active radiation (PAR) is a fundamental variable affecting carbon uptake by ecosystems, not only the total amount but also its spectral distribution and its partitioning between direct and diffuse components. These aspects of PAR are strongly affected by clouds and aerosols. Clouds and aerosols may enhance diffuse PAR, or, in the case of optically thick clouds, they may reflect most of the irradiance out of the atmosphere. Ecosystems, in turn, affect both cloud formation through the process of evapotranspiration and cloud properties by influencing aerosol and water vapor concentrations.

[3] Several researchers have noted that carbon uptake by plants is enhanced on partially cloudy days [*Fitzjarrald et al.*, 1995; *Fan et al.*, 1995; *Gu et al.*, 1999; *Freedman et al.*, 2001; *Gu et al.*, 2002], or specifically on days when the diffuse component of the PAR is enhanced due to atmospheric aerosols or clouds [*Hollinger et al.*, 1994; *Price and Black*, 1990]. Others found that "radiation use efficiency" is higher when diffuse radiation is a higher fraction of the total; that is, diffuse light is used more efficiently [*Rochette et al.*, 1996; *Baldocchi*, 1997; *Choudhury*, 2000]. Furthermore, the spectral distribution of radiation in the PAR domain is important to understand photosynthesis, since action spectra of plants are not uniform across the PAR domain [*Jones*, 1992; *Endler*, 1993]. Microphysics (size distribution and composition) of aerosols and clouds are different, resulting in different spectra reaching the canopy for cloudy or aerosol-laden skies. These studies point to the needs for understanding regional climatology of clouds and aerosols, and for establishing the link between the microphysics of clouds and aerosols, through the PAR irradiance, for CO_2, water vapor and sensible heat exchange.

[4] At Harvard Forest, turbulent fluxes of sensible and latent heat, momentum, and CO_2 are observed continuously from the 30-m level (approximately 5 m above the top of the forest canopy) as well as at 11 m on a tower [*Wofsy et al.*, 1993]. The Harvard Forest site is also equipped with a suite of radiation measurements including upwelling and downwelling shortwave, longwave radiation, PAR, and a multifilter rotating shadowband radiometer (MFRSR). The long-term turbulent exchange and radiation measurements

at Harvard Forest provide a unique opportunity to investigate the effects of aerosols and clouds on CO$_2$ uptake and water use efficiency.

[5] The MFRSR is a seven-channel radiometer with six passbands centered near 415, 500, 610, 665, 862, and 940 nm, and an unfiltered silicon pyranometer [*Harrison et al.*, 1994]. It uses an automated shadowbanding technique to measure the total horizontal, diffuse horizontal, and direct normal spectral irradiances through a single optical path. It guarantees that the separated spectral irradiance components share the same passbands and calibration coefficients; hence the measured surface irradiances are self-consistent and Langley regression applied to the direct beam data can also calibrate the total and diffuse horizontal irradiances against the extraterrestrial spectrum. We take advantage of simultaneous measurements of direct and diffuse spectral irradiances from a MFRSR, to understand the impact of aerosols and clouds on CO$_2$ uptake and water use efficiency, through the PAR irradiance. First we retrieve optical properties of aerosols and clouds to understand characteristics of aerosols and clouds at Harvard Forest [*Min and Harrison*, 1996; *Min et al.*, 2003, 2004]. Second, we synthesize spectra of direct and diffuse from MFRSR measurements, and then we convolve them with an action spectrum of canopy photosynthesis to produce the truly effective action PAR of the canopy (CA_PAR). Finally, in conjunction with turbulent flux measurements at the Harvard Forest site, we study "diffuse use efficiency" and establish the link between the optical properties of aerosols and clouds and CO$_2$ uptake and water use efficiency.

2. Synthesis of the PAR Spectrum From MFRSR Measurements

[6] *Min and Harrison* [1998] developed a rapid inversion algorithm for constructing synthetic terrestrial spectra from measurements made by instruments with multiple narrowband detectors for the ultraviolet domain. It is based on the principle of equivalence in terms of photon path length distribution [*Irvine*, 1964]. For the PAR domain, molecular scattering, ozone absorption, and scattering and absorption of aerosol and cloud primarily determine the atmospheric transmission, while absorptions of water vapor and oxygen bands play minor roles in modulating the transmission. Since the filter passband of MFRSR is 10 nm (much narrower than the spectral variation of optical properties of aerosol and clouds), we can treat the filter function as a δ function. The problem of synthesizing PAR becomes a linear retrieval in ln(transmittance); this is a superposition of apparent optical depths.

[7] With an assumption of constant mean photon path length, the apparent optical depth across the PAR domain can be written as

$$\tau(\lambda) = \sum_{i=0}^{4} x_i \lambda^i + k^{gases}(\lambda)l, \qquad (1)$$

where λ and $k^{gases}(\lambda)$ are the wavelength and the gaseous absorption coefficient in the PAR domain, respectively. For simplicity, we assume the mean photon path length, l, to be the air mass, m. Therefore, for any given channel, we have

$$e_i = b_i - \sum_{i=0}^{4} x_i \lambda^i - k^{gases}(\lambda)m, \qquad (2)$$

where b_i and e_i are measured apparent optical depth as ln(transmittance) and error in the ith channel, respectively. Coefficients, x_i, are evaluated as the least squares minimum of the difference between the measured and modeled apparent optical depths in equation (2). The synthetic spectrum is then

$$\rho(\lambda, x) = S(\lambda) \exp\left[-\sum_{i=0}^{4} x_i \lambda^i - k^{gases}(\lambda)m\right], \qquad (3)$$

where $S(\lambda)$ is the solar spectrum at the top of the atmosphere. Further, the true action PAR of the canopy for a given action spectrum, $A(\lambda)$, can be written as

$$PAR_{CA} = \int_{400nm}^{700nm} A(\lambda)\rho(\lambda, x)d\lambda. \qquad (4)$$

[8] For the spectral synthesis computations we use the Bass and Paur ozone cross sections and the Air Force Geophysics Laboratory (AFGL) midlatitude model [*Anderson et al.*, 1986] to compute the ozone, oxygen and water vapor absorption coefficients as a function of wavelength for one atmospheric path. We use the solar spectrum from MODTRAN [*Berk et al.*, 1989].

[9] To test our retrieval algorithm, we used a collocated MFRSR and a rotating shadowband spectrometer (RSS) at the Atmospheric Radiation Measurement Program (ARM) Southern Great Plains (SGP) site. We selected an optically thick cloudy case with cloud optical depth of 52 at 1800 UTC on 1 December 1997 and a clear-sky case with aerosol optical depth of 0.02 at 1800 UTC on 4 December 1997. Figure 1 shows the comparison of measured and synthesized spectra. The input data of MFRSR measurements are indicated in Figure 1 by letters. The synthesized spectra (dotted lines) for direct, diffuse, and total irradiances under clear-sky and cloudy conditions agree with the measured spectra of the RSS (solid lines) within 2%. Since our interest is in the PAR domain we did not use any channels in the strong water vapor absorption bands; for example, we have no information about water vapor path, and none is needed for this purpose. The comparison validates our synthesis algorithm and demonstrates the accuracy of this fast approach for synthesizing spectra from multifilter narrowband instruments.

3. Influence of Aerosols and Clouds on the PAR

[10] To investigate the impacts of clouds and aerosols on PAR and on carbon uptake quantitatively, we retrieve optical depths of aerosols and clouds from MFRSR measurements. To characterize size of particles in the atmosphere, *Angstrom* [1929] first proposed an empirical relationship between optical depth and wavelengths: $\tau_\lambda = \alpha\lambda^{-\beta}$. The Angstrom exponent coefficient, β, provides a measure of size of particles, i.e., cloud drop (0), aerosols (1–4), and molecular scatterer (4), respectively. We derive the Angstrom exponent coefficient from measurements of MFRSR at 415 and 862 nm. The retrieval algorithms as well as atmospheric classifications are based on spectral and temporal characteristics of radiation measured from a MFRSR [*Min and Harrison*, 1996; *Min et al.*, 2003, 2004]. Figure 2 shows the statistics of optical depths of aerosols, optically thin clouds, and optically thick clouds
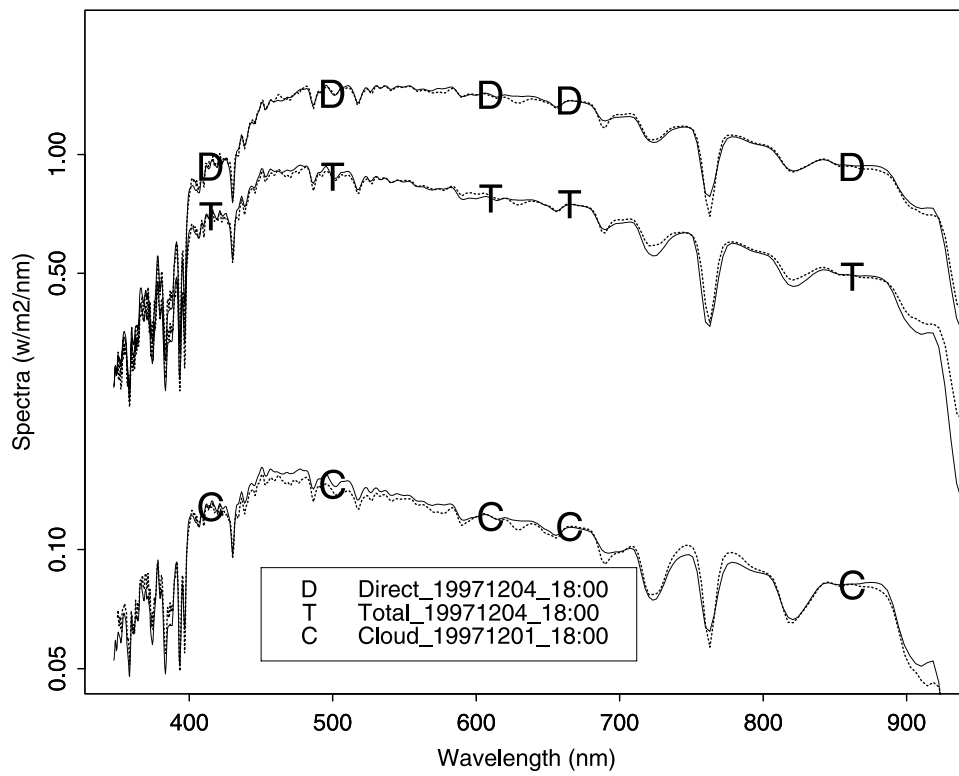
Figure 1. Comparison of measured and synthesized spectra at the Atmospheric Radiation Measurement Program Southern Great Plains site.
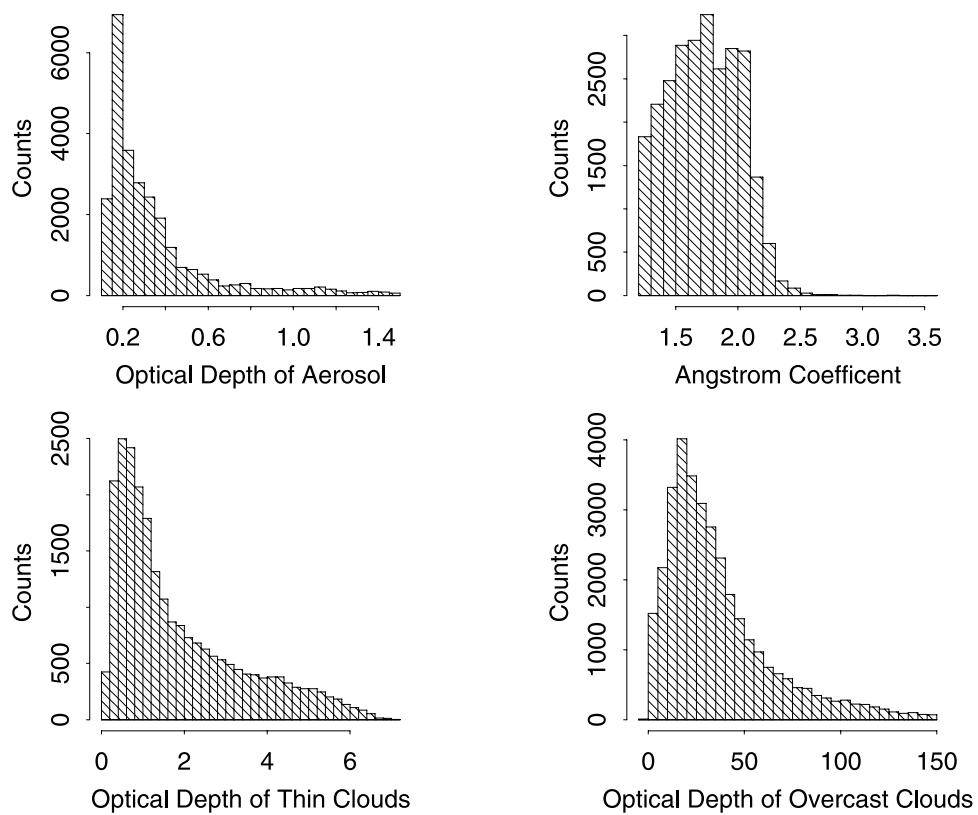

Figure 2. Statistics of optical properties of aerosol, optically thin clouds, and optically thick clouds at Harvard Forest during the growing season of 1998.
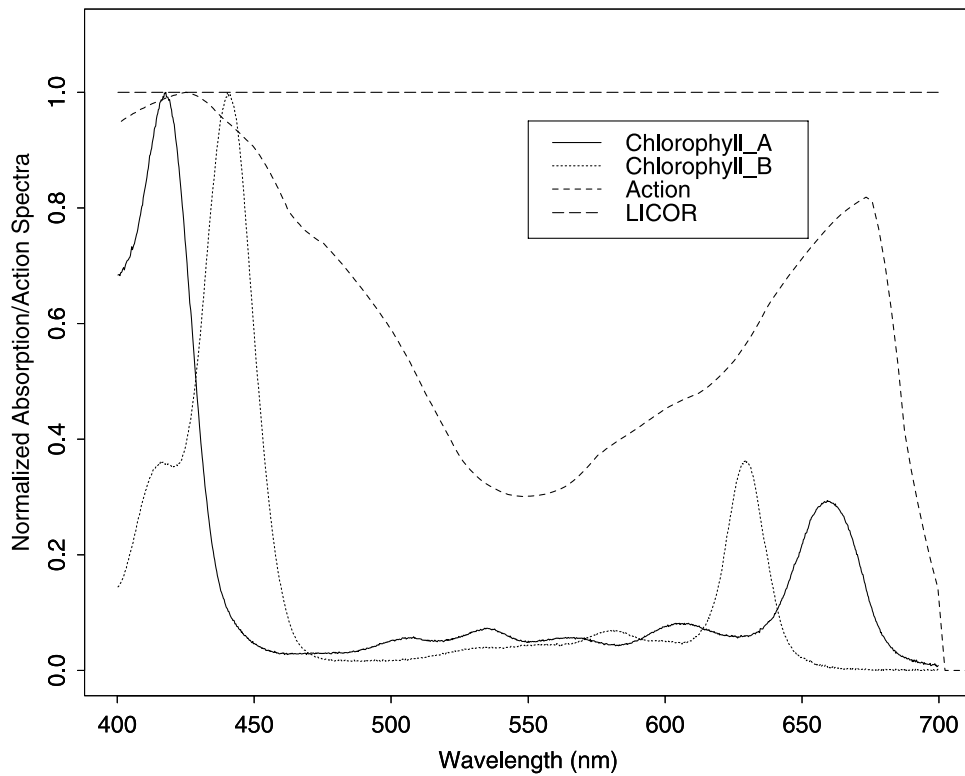
Figure 3. Normalized absorption spectra of chlorophyll-a and chlorophyll-b, the normalized action spectrum, and the normalized response function of LI-COR sensors.

(clouds that completely block direct beam solar radiation) at Harvard Forest during the growing season of 1998. The maximum occurrences of aerosol optical depths and of angstrom exponent coefficients are 0.15 and 1.73, respectively. The probability density distributions of both optically thin and thick clouds are close to gamma distributions, while occurrence of optically thin clouds is much higher than that of optically thick cloud events.
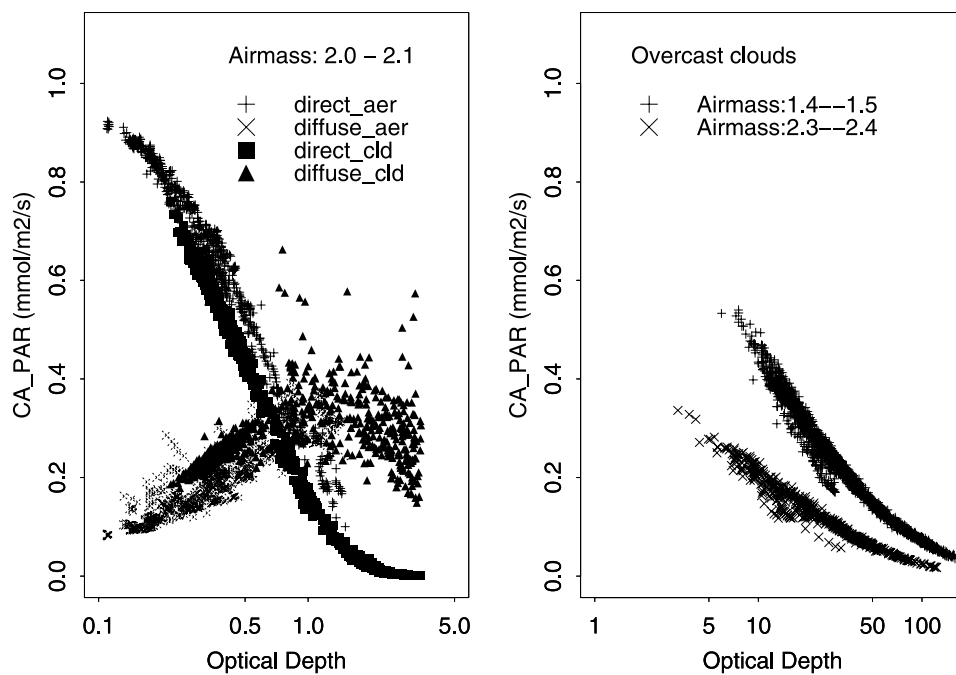

Figure 4. Direct and diffuse CA_PAR versus optical depths of aerosols and clouds under three categories: aerosols, optically thin clouds, and optically thick clouds.
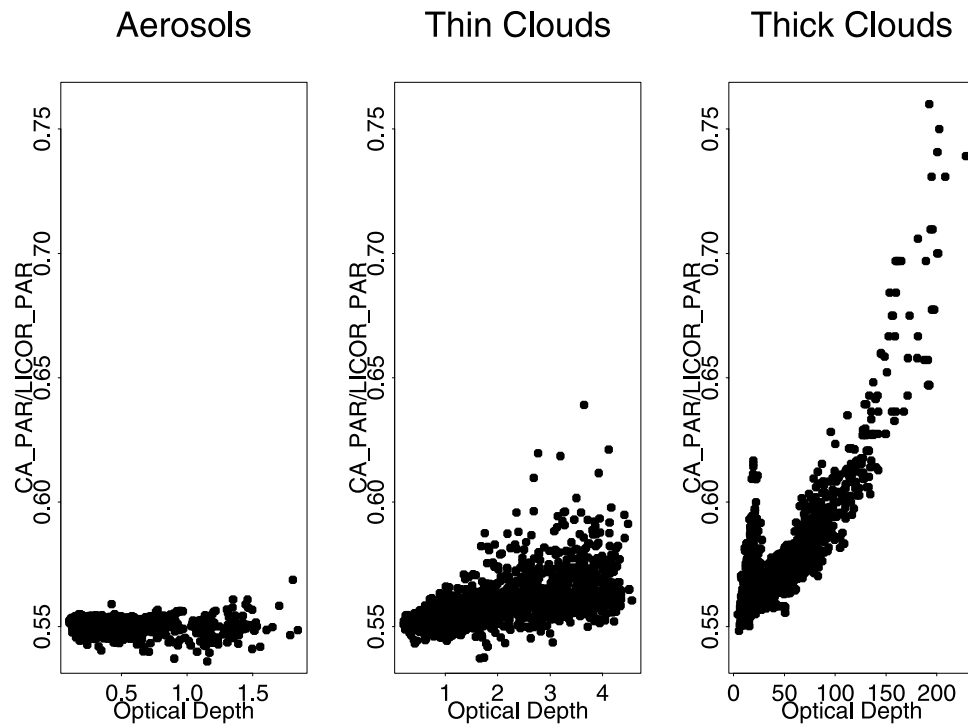
Figure 5. Ratios of CA_PAR to LI-COR_PAR under three sky conditions for solar zenith angles between 55° and 60° during the growing season of 1998 at the Harvard Forest site.

[11] Aerosols and clouds strongly affect spectral distributions of direct and diffuse irradiances in the PAR domain and direct/diffuse partition, which have significant impacts on plant photosynthesis and stresses. After constructing the spectrum and converting to quantum flux from measurements of the MFRSR, we are ready to estimate the action PAR by convolving with the action spectrum of the forest. However, we do not have a realistic action spectrum of canopy photosynthesis at Harvard Forest. We adopt a generic action spectrum of a plant from *Purves et al.* [2004]. Figure 3 shows the normalized action spectrum [*Purves et al.*, 2004], the normalized absorption spectra of chlorophyll-a and chlorophyll-b [*Du et al.*, 1998], and the spectral response of LI-COR sensors. The action spectrum closely follows absorption spectra of chlorophyll-a and chlorophyll-b with broader peaks and valley, as quanta of different wavelengths can be shunted between pigments and enter photosystem I and II. The spectral variation of the normalized action spectrum in the PAR domain magnifies the importance of the spectral distribution of PAR on photosynthesis of canopy. We use this action spectrum as our benchmark to estimate the true action PAR of the canopy (CA_PAR).

[12] Figure 4 shows scatterplots of direct and diffuse CA_PARs against optical depths of aerosols and clouds in three atmospheric categories: aerosols, optically thin clouds, and clouds opaque to direct solar radiation (optically thick clouds). Figure 4 (left) shows the comparison between aerosols and optically thin clouds for solar air masses between 2.0 and 2.1. As we expected, the diffuse CA_PAR increases at small optical depth and then starts to decrease after optical depth is greater than 2.0, while the direct CA_PAR decreases as optical depth increases. For a given

optical depth, the atmosphere loaded with aerosols has higher direct CA_PAR and lower diffuse CA_PAR than with thin clouds. Clouds exhibit relatively constant extinction across the PAR domain with a larger angular-scattering asymmetry factor; aerosols commonly exhibit extinction which substantially decreases with wavelength and a smaller asymmetry factor. This is expected from Mie theory; cloud droplets are much larger than aerosol particles. Thus clouds enhance diffuse irradiance at longer wavelengths more effectively than aerosols. Diffuse CA_PARs may vary more than 100% between cloud and aerosol cases with the same optical depth. The averaged values of direct and diffuse CA_PARs for optical depths between 0.44 and 0.46 are 295 and 187 μmol m^{-2} s^{-1} under aerosol conditions, and 234 and 272 μmol m^{-2} s^{-1} under thin cloud conditions, respectively. The ratio of direct CA_PAR to diffuse CA_PAR dramatically changes from 1.57 under aerosol conditions to 0.86 under thin cloud conditions; that is, the diffuse CA_PAR is substantially enhanced under thin cloud conditions. The total CA_PAR (direct + diffuse) under thin cloud conditions is ~5% more than under aerosol conditions. The CA_PAR also show strong dependence on solar zenith angle, shown in Figure 4 (right); that is, the CA_PAR decreases with increasing of solar air mass (or solar zenith angle) under all conditions.

[13] Some quantum sensors are designed with spectral sensitivity that mirrors the photosynthetic plant response to incident PAR to estimate the quantum flux density. The commonly used LI-COR sensors have a flat spectral response, shown in Figure 3, which is different from the action spectra of plants. To illustrate the importance of spectral variation of PAR, we compare the reconstructed PARs by convolving with the normalized action spectrum
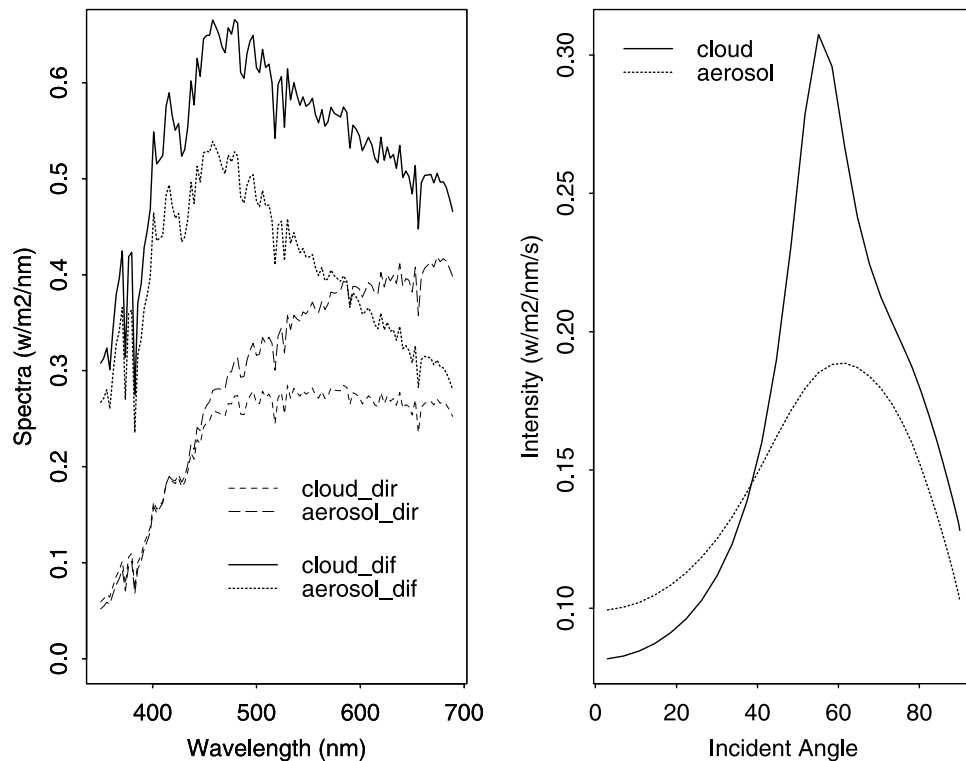
Figure 6. Spectral differences and intensity distributions of direct and diffuse radiations under aerosol and cloud conditions.

(CA_PAR) and the response function of LI-COR sensors (LI-COR_PAR). Figure 5 shows ratios of CA_PAR and LI-COR_PAR under three categories of atmospheric conditions for solar zenith angles between 55° and 60°. This ratio indicates the portion of LI-COR_PAR that is directly involved in the photosynthesis process. Under aerosol conditions, the ratio slightly deceases with increasing of aerosol optical depth. Under optically thin and thick cloud conditions, the ratio increases from 0.55 to 0.75 as cloud optical depth increases. It indicates that spectral distributions of PAR under cloudy conditions are more favorable to plant photosynthesis than under aerosol conditions.

[14] As illustrated by Figures 4 and 5, the direct and diffuse CA_PARs show significant differences due to spectral variations of optical properties of aerosols and clouds. Figure 6 further demonstrates that direct and diffuse spectral irradiances are different under aerosol and thin cloud conditions. These spectral and angular distributions are simulated by an atmospheric radiation transfer model [*Min et al.*, 2004]. In this simulation, we assumed the same total optical depth of 1 at 415 nm for both aerosol and cloud cases. In contrast to direct irradiances, the diffuse irradiance under an aerosol-laden sky is significantly lower than under thin clouds. Leaves of forests do not distinguish photons directly from the sun or scattered in the atmosphere. However, the incident angle of photons at the forest canopy can affect not only how photons penetrate into the forest, but also how photons are intercepted and leaves in the canopy respond. Sunlit leaves, which may receive a high level of direct radiation, will warm up to a higher temperature and are subject to lower photosynthesis rates due to enhanced

respiration and possible photosynthesis saturation. Photons penetrating into the lower part of the canopy thus enhance carbon assimilation. As illustrated by Figure 6 (right), clouds and aerosols affect the diffuse radiation differently and so will have differing impacts on the carbon uptake.

4. Indirect Influences of Aerosols and Clouds on Forest Carbon Uptake

[15] To study the impact of aerosols and clouds on CO₂ uptake we correlate radiation measurements with measurements of turbulent fluxes at Harvard Forest during the growing season of 1998. Radiation measurements were taken every 5 min, the CO₂ and H₂O fluxes were measured every 30 min. Flux measurements were taken with 30-min intervals. Each 30-min period was classified into one of three cases: aerosol, patchy/thin cloud, or thick cloud. If the direct beam components are completely blocked during the 30-min period, it is classified as thick cloud case. Aerosol cases have Angstrom exponents (derived from 415 and 862 nm) greater than 1.2 observed from the direct beam components. Conditions not meeting either of these two tests are classified as patchy/thin cloud cases.

[16] CO₂ uptake is mostly determined by the absorption of PAR. Other factors, such as soil water deficits, temperature, and leaf-to-air vapor pressure deficits (VPD), also influence the photosynthesis process [*Waring and Running*, 1998]. Direct solar radiation subjects leaves at the top of the canopy to high irradiances, warming them. These leaves will experience enhanced respiration, which lowers
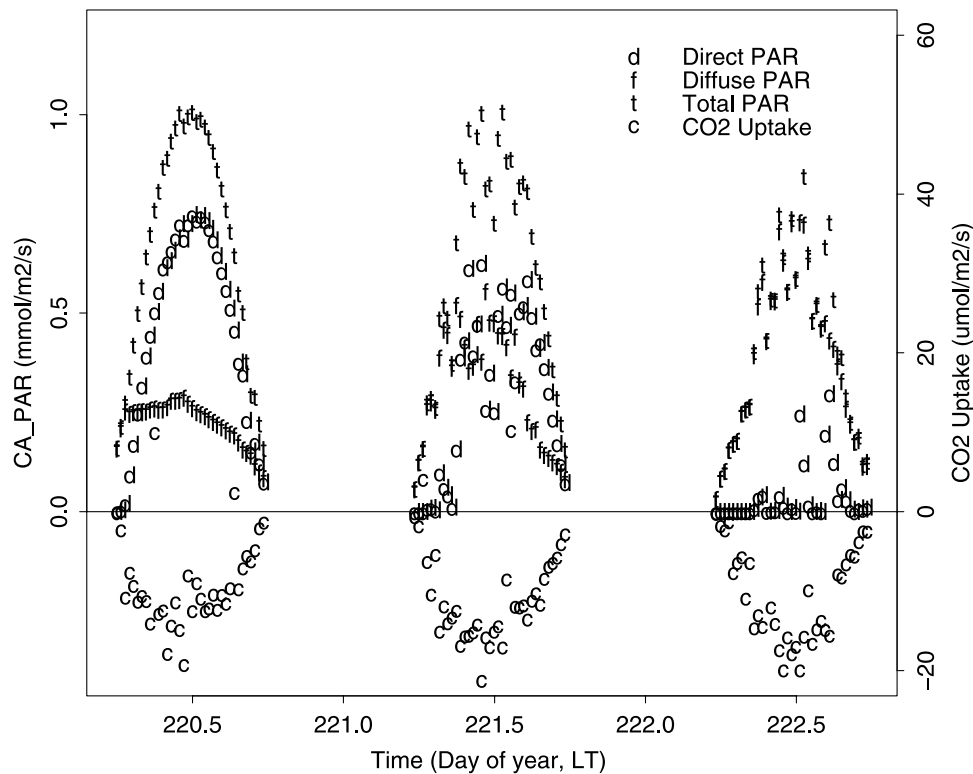
Figure 7. Daily variations of direct, diffuse, and total CA_PAR and carbon uptake for days 220–222, 1998.

rates of net photosynthesis. High leaf temperature and high leaf-to-air VPD can induce moisture stress within the trees over the course of a day, thus limiting stomatal response and reducing carbon assimilations. The presence of clouds affects those factors and subsequently affects carbon uptake. Figure 7 shows daily variations of direct, diffuse, and total CA_PARs and carbon uptake for days 220–222 of 1998. The atmospheric conditions for these three days changed from aerosol, to patchy/thin cloud, and to mostly moderate thick cloud conditions as shown by the CA_PARs. Different influences of aerosols and clouds on CO$_2$ uptake were clearly evident in both short-term carbon uptake (30-min interval) and total daily carbon uptake. The ratio of short-term carbon uptake to CA_PAR (not shown here) systematically increases from day 220 to day 222, indicating carbon uptake efficiency enhanced under cloudy conditions. Daily carbon uptake gradually increased from aerosol to partially cloudy cases, reaching its maximum under morning and midday optically intermittent thick cloud case. Diurnal variations of carbon uptake were also different: asymmetry for the aerosol day (peaked during the midmorning) and symmetry for the optically thick cloudy day, respectively [*Freedman et al.*, 2001]. On day 220, there was high direct solar illumination throughout the day, which led to light saturation and some stomatal closure, reducing carbon uptake in the midday and afternoon periods. On day 222 in contrast, modest thick clouds in the morning blocked direct solar radiation and reduced leaf warming and transpiration, preventing a large increase in water stress within the trees during the day. These

canopy conditions favored stomatal opening and rapid carbon uptake during the afternoon, resulting in a symmetric diurnal variation of carbon uptake. A higher rate of carbon assimilation on the day 222, in conjunction with sufficient PAR radiation under an intermittent cloud cover with modest cloud optical depths, resulted in a higher daily carbon uptake compared to day 220.

[17] Taking advantage of our direct and diffuse measurements and focusing on the issue of "radiation use efficiency", we investigate the relationship between PAR and CO$_2$ uptake for the entire growing season, and further study the impacts of clouds and aerosols on light use efficiency of carbon uptake and water use efficiencies. We seek mean coefficients of diffuse use efficiency, radiation use efficiency of carbon uptake (RUE) and water use efficiency (WUE) over the entire growing season of 1998 under three sky categories: aerosols, patchy/thin clouds, and optically thick clouds (opaque to direct solar radiation). We assume the total effective CA_PAR to be a linear summation of effective direct CA_PAR and diffuse CA_PAR. The "diffuse use efficiency" coefficient, C_{eff}, is determined by a maximum correlation between the total effective CA_PAR and CO$_2$ flux as

$$\mathrm{PAR}_{CA}^{Eff} = \frac{\mathrm{PAR}_{CA}^{dir}}{C_{eff}} + \mathrm{PAR}_{CA}^{dif} \propto \mathrm{Flux}_{CO2}. \qquad (5)$$

[18] Figure 8 shows scattergrams of measured CO$_2$ uptake flux against effective CA_PAR under different

Aerosols

Patchy/Thin clouds
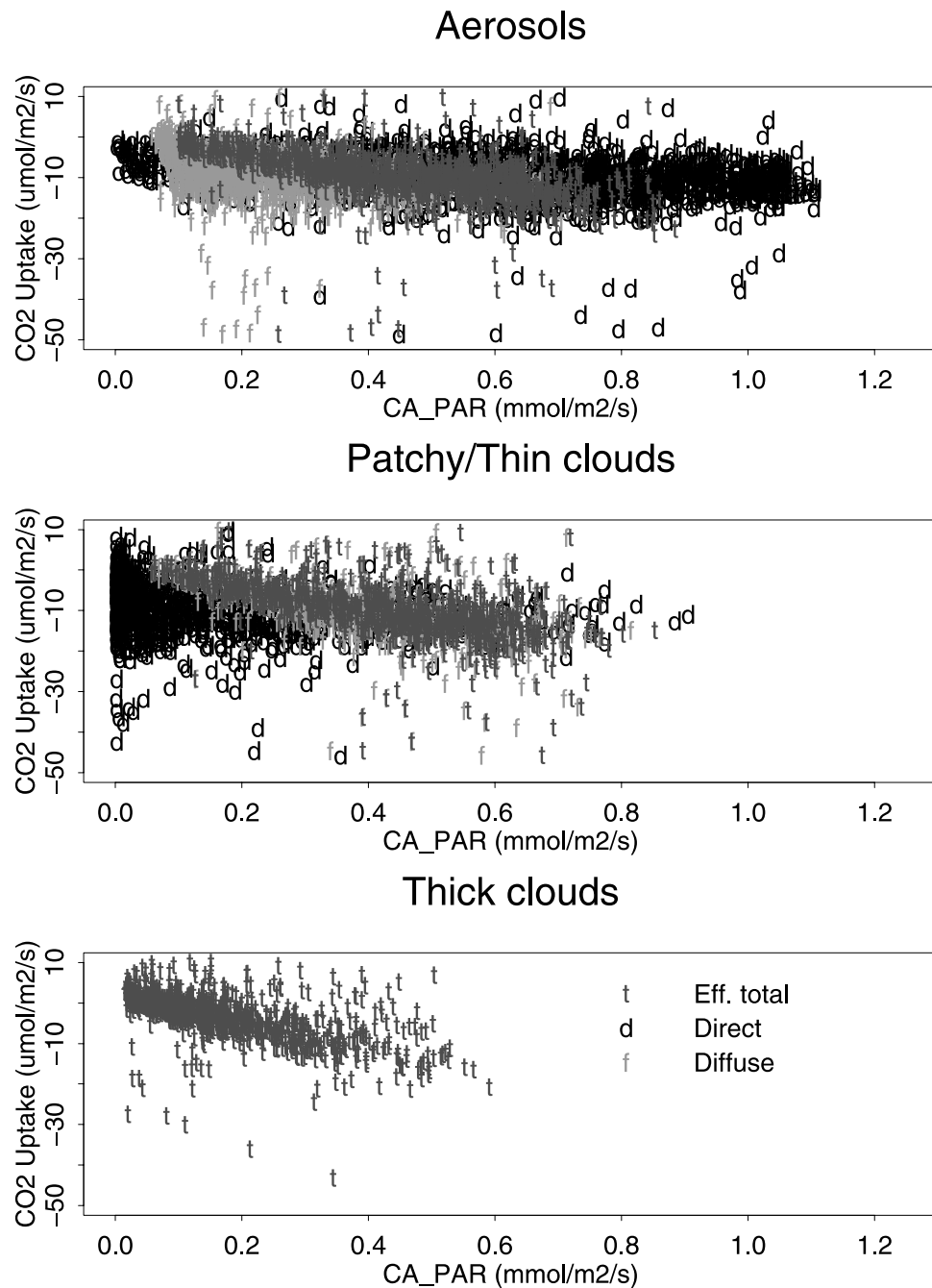

Thick clouds

Figure 8. Scattergrams of direct, diffuse, and effective (eff.) CA_PAR versus measured CO_2 uptake under aerosol, patchy/thin cloud, and optically thick cloud conditions. See color version of this figure at back of this issue.

sky conditions for the growing season of 1998 at the Harvard Forest site. The "diffuse use efficient" coefficients under aerosol and patchy/thin cloud conditions are 1.95 and 3.40 with maximum correlation coefficients of R^2, 0.62 and 0.71, respectively. Under patchy/thin cloud conditions the enhanced diffuse irradiance due to clouds is more efficiently intercepted by the forest and thus increases carbon assimilation. The "diffuse use efficiency" coefficient derived here is, however, an average over a large range of solar zenith angles. The large

scatter of data points in Figure 8 also indicates that other environmental factors have influence on the forest-atmosphere exchange. Eventually we will pursue these issues when we have a statistically significant data set.

[19] Since the RUE depends on radiation level, as the radiation level increases to a certain level, the RUE decreases. It is desirable to use a nonlinear relationship to investigate this issue, particularly under aerosol cases and high radiation levels. We use one linear model and one nonlinear model to fit the relationship between total effec-
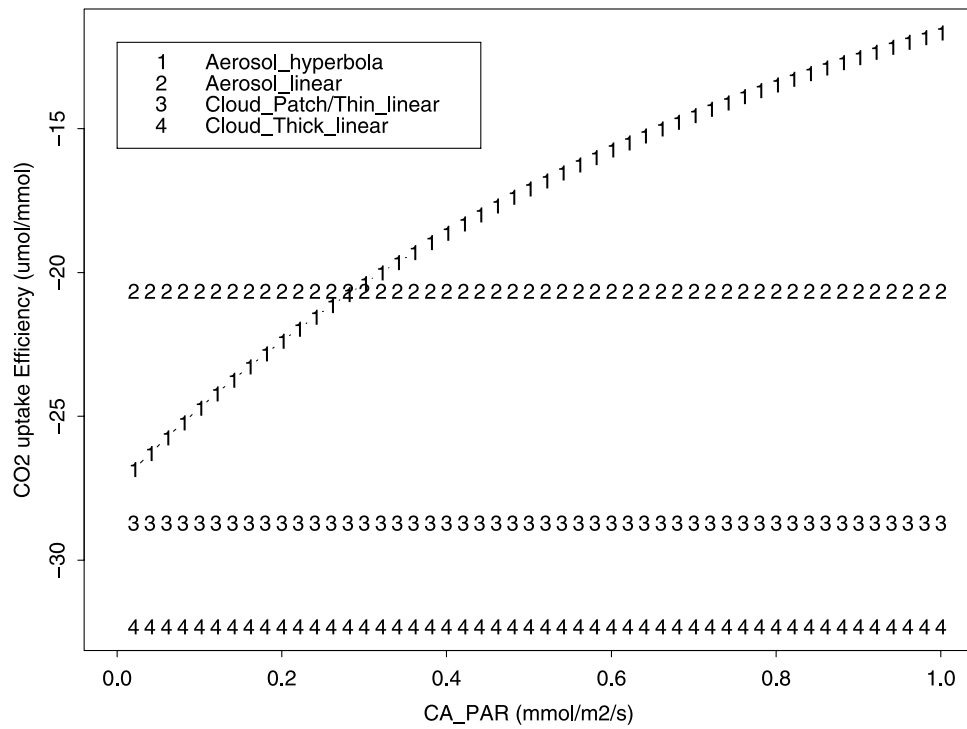
Figure 9. First derivatives (CO$_2$ uptake efficiency) as a function of CA_PAR for various fitting models under aerosol, patchy/thin cloud, and optically thick cloud conditions.

tive CA_PAR and CO$_2$ flux for the entire growing season of 1998:

Linear fit

$$F_{co2} = a + b * \mathrm{PAR}_{CA}^{\mathrm{eff}}$$

Rectangular hyperbolic fit

$$F_{co2} = \frac{a * \mathrm{PAR}_{CA}^{\mathrm{eff}}}{1 + b * \mathrm{PAR}_{CA}^{\mathrm{eff}}}. \qquad (6)$$

[20] The first derivative of fitting function represents the RUE. Figure 9 shows the RUE as a function of CA_PAR under aerosol, patchy/thin cloud, and optically thick cloud conditions for the entire growing season of 1998. We only plot the first derivatives of curvilinear model under aerosol condition where possible photosynthesis saturation might occur. Under aerosol conditions, the first derivative of the rectangular hyperbolic fit is smaller than the linear fit at the higher end of effective CA_PAR but greater than the linear fit

at the lower end of effective CA_PAR. When averaged over the range of effective CA_PAR, the first derivative of the curvilinear fit is close to the value of the linear fit. It is consistent with many studies that show the modeling of canopy photosynthesis over dense forests and crops with longer temporal scales can be simplified by assuming a linear rather than curvilinear relation with incident PAR [*Jarvis and Leverenz*, 1983; *Landsberg*, 1986; *Wang and Polglase*, 1995; *Waring et al.*, 1995; *Ruimy et al.*, 1995; *Waring and Running*, 1998]. The LAI over Harvard Forest after leaf out was over 4 during the growing season of 1998. The RUE of carbon uptake increases from aerosols, patchy/thin clouds, to optically thick clouds, as summarized in Table 1. The RUE under optically thick cloud cases is 57% and 13% higher than under aerosol and patchy/thin cloud cases, respectively. It indicates that an increase of radiation level may not be the only factor responsible for the enhanced carbon assimilation. Changes in many other factors, such as temperature, moisture, latent heat loss, and precipitation, in the presence of clouds may have direct and indirect influences on carbon assimilation, i.e., increasing or decreasing RUE.

Table 1. Diffuse Use Efficiency, Radiation Use Efficiency of CO$_2$ Uptake, and Water Use Efficiency Under Three Categories: Aerosol, Thin and/or Patchy Clouds, and Optically Thick Clouds

	Diffuse Use Efficiency	Radiation Use Efficiency of Carbon Uptake, umol/mmol	Correlation Coefficient (R^2)	Water Use Efficiency, mg/g
Aerosols	1.95	20.6	0.62	5.3
Patchy/thin clouds	3.40	28.7	0.71	8.7
Optically thick clouds	NA[a]	32.3	0.71	26.3

[a]Not applicable.

Aerosols

Patchy/Thin clouds
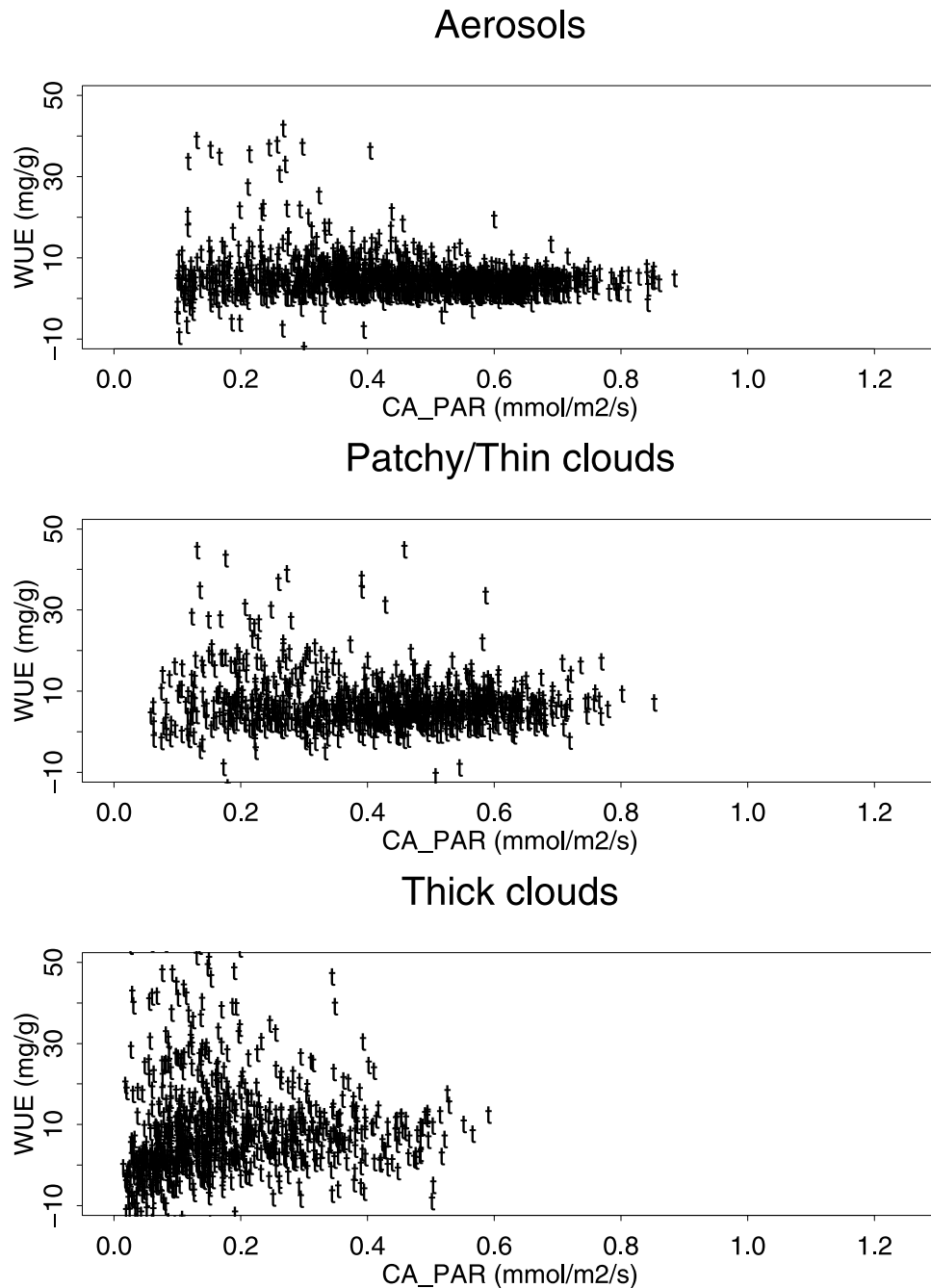

Thick clouds

Figure 10. Scattergrams of total effective CA_PAR versus measured WUE under aerosol, patchy/thin cloud, and optically thick cloud conditions.

[21] As shown in Figure 10 and summarized in Table 1, the averaged WUE over the entire growing season of 1998 is also significantly enhanced as atmospheric conditions change from aerosols to patchy/thin clouds to optically thick clouds. The WUE is defined here in terms of the CO$_2$-water vapor flux ratio over each 30-min interval. The averaged WUE under optically thick cloud condition is almost 5 and 3 times greater than under aerosol and patchy/thin cloud cases, respectively. The primary reasons are that the leaf-to-air VPD in the forest is reduced due to the presence of clouds, and the enhancement of RUE associated with the deeper penetration of light into the forest canopy. In addition to changes in moisture, the presence of clouds can both cause and be the consequence of changes in many atmospheric factors such as temperature, latent heating, leaf-to-air VPD, and stomatal dynamics.

5. Discussion and Summary

[22] The impact of aerosols and clouds on CO$_2$ uptake and water use efficiency at Harvard Forest has been studied by using collocated turbulent flux and radiation measurements. Taking advantage of simultaneous measurements of direct and diffuse spectral irradiances from a MFRSR, we quantitatively studied issues of "diffuse use efficiency",

RUE of CO_2 uptake and WUE and cataloged the impact of aerosols and clouds through photosynthesis on CO_2 uptake.

[23] We have developed a fast retrieval algorithm for synthesizing the visible spectrum from multinarrowband instruments and applied it to predict the Action PAR for both direct and diffuse components by convolving with a normalized action spectrum of plants. Validations based on a collocated MFRSR and spectrometer demonstrated accuracy of 2% under various sky conditions. Based on the measurements during the growing season of 1998, we characterized atmospheric conditions of aerosols and clouds at Harvard Forest: The mean optical depths and angstrom exponent coefficients of aerosols are 0.15 and 1.73, respectively. The probability density distributions of both optically thin and thick clouds are close to gamma distributions. The occurrences of patchy/thin clouds are much higher than that of optically thick events, in part due to forest induced boundary layer cumulus clouds [*Freedman et al.*, 2001].

[24] By combining observation and modeling, we found that optical properties of aerosols and clouds have significant impacts on photosynthesis not only through changes of the total amount of PAR, but also through changes of its spectral distributions (or light quality) and its partitioning between direct and diffuse components. The diffuse CA_PAR with a broader angular distribution is more effectively intercepted by the forest than the direct CA_PAR, resulting in enhanced carbon assimilation. The diffuse PAR is much greater under patchy/thin cloud condition than under aerosol condition for a given optical depth. The enhanced diffuse PARs under cloudy conditions have spectral distributions that are more favorable to the photosynthesis process. This study illustrates the needs for simultaneous measurements of direct and diffuse spectral radiation in the PAR domain to investigate photosynthetic processes.

[25] We also derived "diffuse use efficiency" based on the maximum correlation between CO_2 uptake and total effective CA_PAR. The "diffuse use efficiency" shows a strong dependency on atmospheric conditions: much higher for partial/thin clouds (3.4) than for aerosols (1.9). Furthermore, the RUE of carbon uptake increases from aerosols, patchy/thin clouds, to optically thick clouds. Under optically thick clouds the CO_2 uptake efficiency is about 57% and 13% higher than under aerosol and patchy/thin clouds, respectively. The WUE also shows significant enhancement as atmospheric conditions change from aerosol to optically thick clouds. The WUE under optically thick clouds is almost 5 and 3 times greater than under aerosol and patchy/thin clouds, respectively. We may conclude that an increase of radiation level might not be the only factor responsible for the enhance carbon assimilation. Changes in many other factors, such as temperature, moisture, latent heating, and precipitation, in the presence of clouds may have direct and indirect influences on carbon assimilation and water use efficiency.

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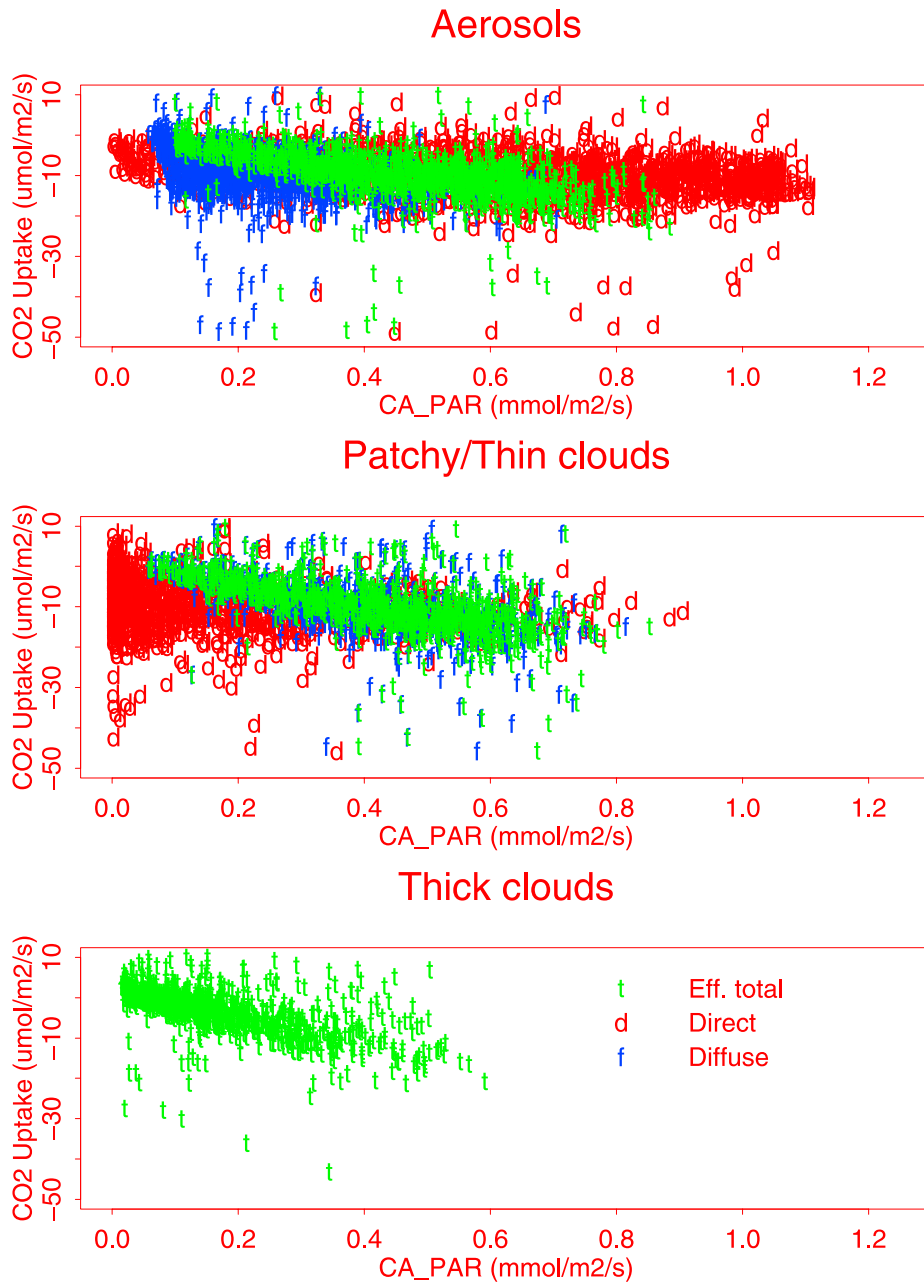
Figure 8. Scattergrams of direct, diffuse, and effective (eff.) CA_PAR versus measured CO$_2$ uptake under aerosol, patchy/thin cloud, and optically thick cloud conditions.