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Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: Results from two North American deciduous forests

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Abstract. We analyzed half-hourly tower-based flux measurements of carbon dioxide (CO_2) from a boreal aspen forest and a temperate mixed deciduous forest in Canada to examine the influences of clouds on forest carbon uptake. We showed that the presence of clouds consistently and significantly increased the net ecosystem exchanges (NEE) of CO_2 of both forests from the level under clear skies. The enhancement varied with cloudiness, solar elevation angles, and differed between the two forests. For the aspen forest the enhancement at the peak ranged from about 30% for the 20°–25° interval of solar elevation angles to about 55% for the 55°–60° interval. For the mixed forest the enhancement at the peak ranged from more than 60% for the 30°–35° interval of solar elevation angles to about 30% for the 65°–70° interval. Averaged over solar elevation angles >20°, the aspen and mixed forests had the maximal NEE at the irradiance equivalent to 78 and 71% of the clear-sky radiation, respectively. The general patterns of current sky conditions at both sites permit further increases in cloudiness to enhance their carbon uptake. We found that both forests can tolerate exceedingly large reductions of solar radiation (53% for the aspen forest and 46% for the mixed forest) caused by increases in cloudiness without lowering their capacities of carbon uptake. We suggest that the enhancement of carbon uptake under cloudy conditions results from the interactions of multiple environmental factors associated with the presence of clouds.

1. Introduction

Clouds, as a natural weather element at a given location, strongly influence environmental conditions on the ground surface via radiative transfer, latent heating, and precipitation [*Benner and Curry*, 1998]. Therefore it is expected that clouds can have important ramifications on CO_2 exchanges between terrestrial ecosystems and the overlying atmosphere. Field observations have shown that the highest rate of forest net ecosystem exchanges (NEE) of CO_2 (i.e., the most negative value, following the NEE sign convention) often occurs on cloudy rather than on sunny days [*Price and Black*, 1990; *Hollinger et al.*, 1994; *Fitzjarrald et al.*, 1995; *Sakai et al.*, 1996; *Freedman et al.*, 1998]. Other studies have found that for a given irradiance level, overcast days generally have a higher NEE rate (in terms of the absolute value) than clear days [*Fan et al.*, 1995; *Baldocchi*, 1997; *Goulden et al.*, 1997]. To explain such observations, several mechanisms have been postulated. They include increases in diffuse radiation [*Price and Black*, 1990; *Hollinger et al.*, 1994; *Fan et al.*, 1995; *Goulden et al.*, 1997], decreases in the respiration of sunlit leaves [*Baldocchi*, 1997], reduction in vapor pressure deficit (VPD) [*Freedman et al.*, 1998], and stomatal dynamics associated with light fluctuations [*Fitzjarrald et al.*, 1995; *Sakai et al.*, 1996]. Although observed at stand levels through tower-based flux measurements, the enhancement of carbon uptake under cloudy conditions has regional and global implications because cloudiness has been increasing over many regions of the world [*McGuffie and Henderson-Sellers*, 1988; *Henderson-Sellers*, 1989; *Karl and Steurer*, 1990; *Russak*, 1990; *Angell*, 1990; *Kaiser and Razuvaev*, 1995; *Abakumova et al.*, 1996]. It is of particular interest in North America where increased vegetation activities have been observed [*Keeling et al.*, 1996; *Myneni et al.*, 1997] and a terrestrial carbon sink has been suggested by eddy covariance measurements [*Wofsy et al.*, 1993], isotopic analyses of atmospheric CO_2 [*Ciais et al.*, 1995], and modeling studies [*Fan et al.*, 1998], while increases in cloudiness have been observed [*McGuffie and Henderson-Sellers*, 1988; *Henderson-Sellers*, 1989; *Karl and Steurer*, 1990; *Angell*, 1990].

At present, we lack systematic approaches to examine the relationship between carbon uptake by terrestrial ecosystems and cloudiness. Previous studies focused on the comparison between two categories of sky conditions: cloudy (overcast) and clear days. The comparison was either on an individual day basis [*Price and Black*, 1990; *Hollinger et al.*, 1994; *Fitzjarrald et*

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al., 1995; *Sakai et al.*, 1996] or on a multiple-day/seasonal basis [*Fan et al.*, 1995; *Baldocchi*, 1997; *Goulden et al.*, 1997; *Freedman et al.*, 1998]. In the latter case, the differences between overcast and clear days were often shown through the NEE-photosynthetically active radiation (PAR) relationship. These comparisons show straightforwardly differences in the carbon uptake between sunny and overcast days. However, two important methodological issues have yet to be solved. First, the classification of sky conditions into merely two categories is an oversimplification of the real situation. It is critical to know how gradual changes in sky conditions affect the carbon exchange. Second, the effect of solar elevation angles on canopy photosynthesis should be teased out from the influence of clouds on the carbon exchanges. As the solar elevation angle increases, the proportion of the light reaching deeper canopies also increases because of the reduced light extinction [*Ross*, 1981; *Campbell and Norman*, 1989]. Consequently, the radiation use efficiency increases with solar elevation angles [*Gu et al.*, 1999]. In order for an overcast day to have the same solar radiation level as a clear day the Sun must be in a higher position. Therefore the higher NEE rate found under the overcast condition at the same radiation level with the sunny condition can be partly attributed to the increase in the radiation use efficiency of direct beam with solar elevation angles. To solve these issues, new approaches are needed.

The three major objectives in this study are as follows: (1) to develop a methodology for the study of the relationship between cloudiness and the carbon uptake by terrestrial ecosystems, (2) to quantify the influences of clouds on carbon uptakes by two North American deciduous forests, and (3) to identify potential factors contributing to and controlling the response of forest carbon uptake to changes in cloudiness. In particular, we want to answer the following questions. Is the enhancement in forest CO_2 uptake on cloudy days consistent over time and statistically significant? What is the optimal sky condition for forest carbon uptake? Obviously, forest carbon uptake is hindered if the clouds are too thick and the PAR is reduced too much. Then it is logical to ask at what threshold clouds become limiting factors for forest carbon uptake? Given the observed trends of increasing cloudiness over many regions of the world [*McGuffie and Henderson-Sellers*, 1988; *Henderson-Sellers*, 1989; *Karl and Steurer*, 1990; *Russak*, 1990; *Angell*, 1990; *Kaiser and Razuvaev*, 1995; *Abakumova et al.*, 1996], we also want to know if the current levels of cloudiness, as observed at these two sites, allow for further increases in cloudiness to enhance forest carbon uptake. To achieve these objectives and to answer these questions, we use long-term half-hourly eddy covariance flux and meteorological measurements from two contrasting North American deciduous forests as bases for analyses.

2. Materials and Methods

In this section we describe the sites where long-term NEE measurements were obtained and the data sets included in this study. Also, we outline the developed analytical procedures to ascertain the influence of clouds on the NEE.

2.1. Site Descriptions and Field Measurements

The data included in this study were obtained at two Canadian deciduous forests. One forest (northern) is located in the Prince Albert National Park, Saskatchewan, Canada. It consists primarily (>90%) of trembling aspen (*Populus tremuloides*) and is located in the southern boreal forest of Canada (53°63′N, 106°20′W) away (>300 km) from anthropogenic activities. Randomly located throughout the landscape, the forest also includes a small percentage (<8%) of balsam poplar (*Populus balsamifera*), white spruce (*Picea glauca*), and black spruce (*Picea mariana*). During the 1994 growing season the height of this 70-year-old aspen forest averaged 22 m, and it had a final leaf area index (LAI) of 2.4. The canopy architecture featured an open trunk space between 2 and 15 m without foliage, and aspen leaves were distributed in the layer between 15 and 22 m. Between the ground and 2 m, a hazelnut (*Corylus cornuta*) understory with a LAI of 3.2 [*Black et al.*, 1996] existed throughout the landscape. More details about the characteristics of this site can be found elsewhere [*Black et al.*, 1996; *Blanken et al.*, 1997; *Fuentes et al.*, 1999; *Simpson et al.*, 1997]. The second forest (southern) is located at Camp Borden (44°19′N, 80°56′W), Ontario, Canada, and impacted by anthropogenic activities. It is a temperate mixed forest. On the basis of a survey conducted during 1995 this 90-year-old forest comprises red maple (*Acer rubrum*) 35.8%, trembling aspen (*Populus tremuloides*) 8.2%, big-tooth aspen (*Populus grandidentata*) 21.9%, white ash (*Fraxinus americana*) 11.5%, black cherry (*Prunus serotine*) 0.7%, birch (*Betulia populifolia*) 13.3%, and beech (*Fagus drandifolia*) 8.6%. During the 1995 growing season the forest canopy averaged 22 m high and had a LAI of 4.2. More details on the characteristics of this site can be found elsewhere [*Neumann et al.*, 1989; *Fuentes and Wang*, 1999]. Using scaffold towers as measurement platforms, continuous eddy covariance fluxes for momentum, virtual heat, carbon dioxide, and water vapor were determined using three-dimensional sonic anemometers (model DAT-310, Kaijo Denki Ltd., Tokyo, Japan) in combination with appropriate fast-response gas analyzers (model LI-6262, LiCor Inc., Lincoln, Nebraska). The data were acquired at 100 Hz and block averaged to 20 Hz. From the raw data, half-hourly fluxes were calculated. At both sites the ecosystem carbon dioxide fluxes were measured using an eddy covariance system deployed above the canopy [*Black et al.*, 1996; *Fuentes and Wang*, 1999; *Lee et al.*, 1999]. To examine the environmental controls on the forest NEE, microclimate measurements above and within the forests were made at both sites, utilizing identical measurement systems. Measurements of air temperature (using ventilated copper-constantan thermocouples) at 12 levels above ground, wind speed and direction (R.M. Young anemometer model 0571, Traverse City, MI) at 45 m, incoming solar irradiance (W m^{-2}, radiant flux density on a horizontal surface) (model PSP pyranometer, Eppley Laboratory, Newport, Rhode Island), PAR (model LI190SA, LiCor Inc.) above the forest, and relative humidity (model MP-100, Rotronic Instrument Corp., Huntington, New York) at two levels above the forests were taken throughout the growing season. The Eppley radiometer provided the total (direct plus diffuse) incoming solar radiation, and the quantum sensor gave the total photosynthetically active radiation above the forests. For both forests, only midgrowing season data were used in this study to largely eliminate the effect of changing LAI. The periods of constant LAI were days 160–240 for the boreal aspen forest in 1994 and days 160–260 for the temperate mixed forest in 1996 and 1997 [*Black et al.*, 1996; *Fuentes and Wang*, 1999; *Fuentes et al.*, 1999].

Table 1. Regressional Coefficients of Relationships Between Clear-Sky Irradiance and Sine of Solar Elevation Angles (Equation (2)) As Well As Relationships Between Clear-Sky Clearness Index and Sine of Solar Elevation Angles (Equation (5)) for Mornings and Afternoons of Growing Seasons at the Boreal Aspen Site in 1994 and the Temperate Mixed Forest Site in 1997

Regressional Coefficients	Aspen Forest in 1994		Mixed Forest in 1997	
	Morning	Afternoon	Morning	Afternoon
a_0	650.10	751.89	675.55	754.36
b_0	442.10	327.52	393.68	323.35
r^2	1.00	1.00	1.00	1.00
a_1	1.15	0.98	2.02	1.12
b_1	−0.88	−0.85	−2.63	−1.15
c_1	0.19	0.23	1.26	0.46
y_1	0.29	0.39	0.17	0.37
r^2	0.96	0.77	0.98	0.97

2.2. Data Analysis Procedures

Since no direct cloud observations were made at both sites, we used the measured global solar radiation at the ground surface to define the presence of clouds. The critical step in this approach is to identify the clear skies so that the basis for comparisons can be established. Once the clear skies are identified, the other days can be assumed to be cloudy days with varying amounts of clouds in the sky. Using the clear-sky global solar radiation as a reference, the global solar radiation under the cloudy skies provides a measure of cloudiness. In the following presentation of our data analysis procedures, we first introduce two variables that we use to quantify cloudiness. Then we describe the standards we set for clear skies and steps for identification. The rest explains how the influences of clouds on the NEE are examined and what environmental factors we are looking at for possible explanations.

2.2.1. Quantification of cloudiness. The word of "cloudiness" is often used as the same for "cloud cover" (that portion of the sky cover which is attributed to clouds, usually measured in tenths of sky covered). However, in this paper it is used in a very general sense and refers to the presence, quality, and quantity of clouds in the sky. A useful variable for the study of influences of clouds on the carbon uptake is the ratio of the total irradiance received under a given sky condition to the clear-sky irradiance (see section 2.2.2 for the definition of clear skies) multiplied by 100. In this paper we call this value "relative irradiance" denoted by r:

$$r = 100 \times \frac{S}{S_0}, \quad (1)$$

where S is the total irradiance received under a given sky condition (W m^{-2}), and S_0 is the clear-sky irradiance (W m^{-2}). To calculate r, S_0 must be known first. A few empirical clear-sky irradiance models are available in the literature [*Gates*, 1980; *Duchon and O'Malley*, 1999]. However, at both the boreal site and the temperate site we found that the clear-sky irradiance (see section 2.2.2 for the definition of clear-sky irradiance) can be predicted from the solar elevation angle by the following quadratic polynomial as in (2):

$$S_0 = a_0 \sin \beta + b_0 \sin^2 \beta \quad (2)$$

where β is the solar elevation angle calculated by using an algorithm given by *Meeus* [1985]; a_0 and b_0 are site- and morning- and afternoon-specific regressional coefficients, and their values for the boreal and temperate sites are given in Table 1. Figure 1 shows the measured and fitted relationships between the clear-sky irradiance and the sine of solar elevation angle for the boreal site (Figure 1a) and the temperate site (Figure 1b). The clear-sky irradiance is slightly asymmetrical between the morning and the afternoon. For a given solar elevation the clear-sky irradiance in the afternoon tends to be higher than in the morning.

Although the relative irradiance gives a straightforward representation of changes in solar radiation associated with

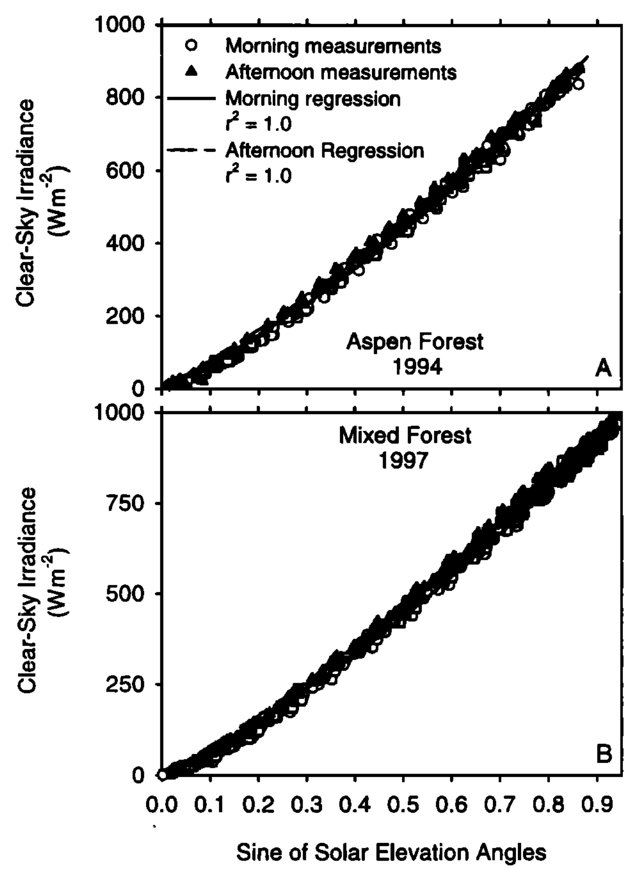

Figure 1. Scatterplots and regressions between the clear-sky total irradiance and the sine of solar elevation angles for (a) the boreal aspen forest in 1994 and (b) the temperate mixed forest in 1997. The irradiance was measured over the canopy. The data are fitted by equation (2).

changes in cloudiness, it requires the clear-sky irradiance, which may not be readily available. Alternatively, sky conditions can be described by the clearness index. It is defined as the ratio of global solar radiation received at the Earth surface to the extraterrestrial irradiance at a plane parallel to the Earth surface. The concept of clearness index has been used widely by solar energy engineers [*Liu and Jordan*, 1960; *Reindl et al.*, 1990; *Moriarty*, 1991; *Ianetz and Kudish*, 1994; *Lam and Li*, 1996]. It is calculated by

$$k_t = \frac{S}{S_e}, \quad (3a)$$

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

where k_t denotes the clearness index, S_e denotes the extraterrestrial irradiance at a plane parallel to the Earth surface (W m^{-2}), S_{sc} is the solar constant (1370 W m^{-2}), and t_d denotes the day of year. The relative irradiance r is related to k_t by the following relationship:

$$r = \frac{S}{S_0} = \frac{k_t S_e}{k_{t0} S_e} = \frac{k_t}{k_{t0}}, \quad (4)$$

where k_{t0} is the clear-sky clearness index.

While the relative irradiance is affected only by cloudiness, the clearness index changes with solar elevation angles as well as cloudiness. Under clear skies the clearness index increases with solar elevation. Similarly to the clear-sky irradiance S_0, we use the following cubic polynomial to fit the clear-sky clearness index k_{t0} from sin β:

$$k_{t0} = y_1 + a_1 \sin \beta + b_1 \sin^2 \beta + c_1 \sin^3 \beta, \quad (5)$$

where y_1, a_1, b_1 and c_1 are site- and morning- and afternoon-specific regressional coefficients, and their values for the boreal and temperate sites are given in Table 1. Figure 2 shows the calculated and fitted relationships between k_{t0} and sine of solar elevation angles for the boreal site (Figure 2a) and the temperate site (Figure 2b). Again, asymmetry exists between the morning and the afternoon clear skies. For a given solar elevation angle the afternoon clear-sky clearness index is generally larger than the morning clear-sky clearness index, especially when solar elevation angles are low (Figure 2). The asymmetry is enlarged as compared with the case of irradiance.

At a given solar elevation angle a decrease in the clearness index generally indicates an increase in cloud thickness. However, exception occurs when clouds are not distributed continuously over the sky. The sunlit ground surfaces, which are located at the end of paths of solar beams passing through gaps formed by individual clouds in neighboring skies, may actually receive more irradiance than under a clear sky because of light reflections from the sides of clouds [*Duchon and O'Malley*, 1999]. In this paper we call this phenomenon the "cloud gap effect." By analyzing data given by Duchon and O'Malley we found that the cloud gap effect may increase ground surface irradiance by more than 20%. The cloud gap effect tends to increase the clearness index, and this increase is not an indication of improvement in sky "clearness." However, we can detect the cloud gap effect by using the clear-sky clearness index as a criterion. This will be discussed later in detail.

In this study, the influences of clouds on the carbon uptake will be analyzed mainly in terms of changes of the NEE and environmental factors with the clearness index. The relationships between the NEE and the relative irradiance, which is a more direct indication of changes in solar radiation as a result of changes in cloudiness than the clearness index, will be used to determine the optimal and critical radiation environments for the carbon uptake.

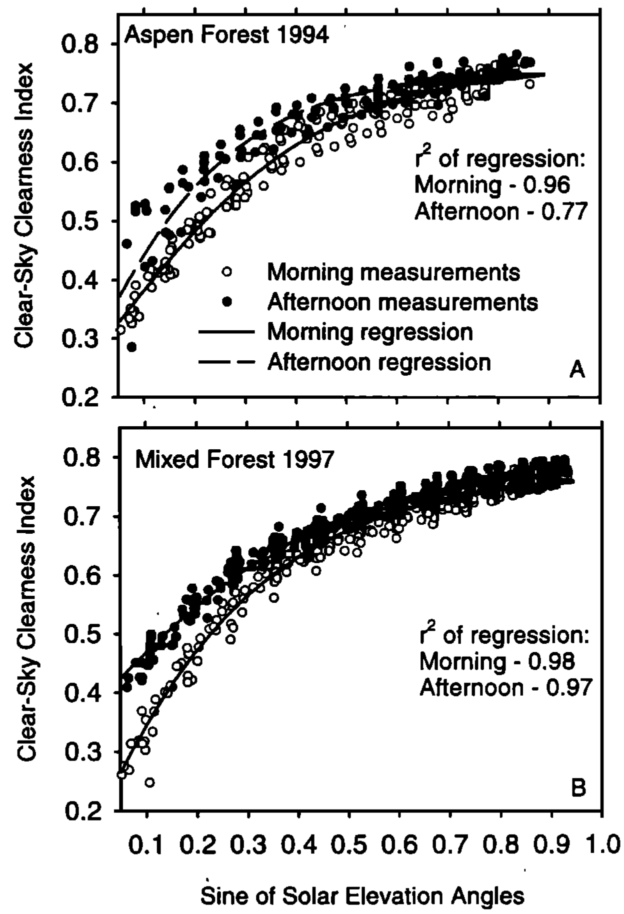

Figure 2. Scatterplots and regressions between the clear-sky clearness index and the sine of solar elevation angles for (a) the boreal aspen forest in 1994 and (b) the temperate mixed forest, 1997. The data are fitted by equation (5).

2.2.2. Defining clear skies. To quantify the influences of clouds on the NEE of CO_2, we set the clear-sky NEE as a baseline for comparison. A clear sky was identified on a half-day basis. We took this half-day classification because days with no clouds for the whole daytime were rare. We set the following two standards for clear mornings and afternoons: (1) k_t must increase smoothly with sinβ and (2) the relationship between clear-sky k_t and sinβ must form an envelope in the lumped scatterplot of k_t against sinβ. The following procedure was applied: First, values of the clearness index were plotted against time, and these mornings or afternoons with smoothly changing values of the clearness index were selected. Then, values of the clearness index of the selected mornings or afternoons were plotted against solar elevation angles on the same plot. The mornings or afternoons with their relations of the clearness index and the solar elevation angle falling away from the major patterns were excluded. Finally, the clearness index was plotted against the solar elevation angle on the same plots for all mornings and afternoons in the growing season to make sure the identified relationship between the clear-sky clearness index and the solar elevation angle forms the envelope for the scatter points on the plots. We had also tried using the total irradiance instead of the clearness index in this process and found that it does not provide an indication of the presence of clouds as sensitively as the clearness index. For example, if a relatively thin cloud moves into the path of a solar beam, the time series of irradiance may still be smooth, but the change in the clearness index can easily be detected. This is due to the fact that the clearness index is a pure indication of atmospheric thickness, while the total solar radiation at the surface is a function of both the atmospheric thickness and the extraterrestrial solar radiation on a plane parallel to the Earth surface, which changes with solar elevation angles.

2.2.3. Examining influences of clouds on the NEE. For cloudy skies we further distinguish two situations because of the cloud gap effect. As shown later, no matter whether the site is under a cloud gap or directly under a cloud shade, the carbon uptake tends to be enhanced. However, the radiation regime over a site under a cloud gap is different from the radiation regime when the site is directly under a cloud shade. Although in both situations the diffuse radiation can be enhanced, the ground surface under a cloud gap receives the same amount of direct beam radiation as under the clear sky, while under a cloud shade, the direct beam radiation is reduced. Therefore we separate the ground conditions under patchy cloudy skies into two types: cloud-gap condition and cloud-shade condition. For a fixed point on the ground, the surface may experience alternatively cloud-gap and cloud-shade conditions due to the movement of clouds and the rotation of the Earth. In this study, cloud-gap and cloud-shade conditions were separated from each other by using the clear-sky relationship between the clearness index and the solar elevation angle as a criterion. The measurements with the clearness index larger than the clear-sky values at the same solar elevation angles were treated as cloud-gap measurements. The rest of the measurements from cloudy days were treated as cloud-shade quantities. To determine the magnitude of the influence of clouds on the NEE, changes in the NEE relative to clear skies (%NEE) were calculated by the following relationship:

$$\%\mathrm{NEE} = 100[F(\beta) - F_c(\beta)]/F_c(\beta), \tag{6}$$

where $F(\beta)$ is the measured NEE under a given sky condition, and $F_c(\beta)$ is the NEE calculated from the regressional relationship between the measured clear-sky NEE and the solar elevation angle β.

To largely eliminate the interference of solar elevation angles on the analyses of changes of the NEE or %NEE with the clearness index or relative irradiance, we grouped the data into 5° intervals of solar elevation angles. It should be noted that the interval of 5° was chosen empirically. It is a trade-off between two opposing factors. On the one hand, the interval should be larger enough so that sufficient amount of samples can be included for statistical analyses. On the other hand, it must be small enough so that changes in the NEE or %NEE with the clearness index or relative irradiance reflect the response of the ecosystem to changes in cloudiness rather than to changes in solar elevation angles.

We also introduced two useful concepts to evaluate the relationship between the NEE and the solar radiation environments perturbed by clouds: optimal relative irradiance and critical relative irradiance. The optimal relative irradiance is defined as the relative irradiance at which the NEE rate reaches its maximum at a given solar elevation angle. The critical relative irradiance is defined as the relative irradiance under a cloudy sky that produces the same NEE rate as under a clear sky.

Although we defined clear skies on a half-day basis, we did not distinguish between morning and afternoon in our analyses except when only clear-sky relationships were concerned. The exposition of the asymmetry between morning and afternoon for changes of solar radiation, clearness index, NEE of CO_2, etc., with solar elevation angles is meaningful only for clear-sky conditions. When clouds are introduced, the basis for the comparison is lost.

2.2.4. Environmental factors. To identify potential factors controlling and contributing to the influence of clouds on the carbon uptake, we also studied relationships between the clearness index and the total PAR, diffuse PAR, VPD, air temperature, and soil temperature. At both sites the diffuse PAR was not measured. Therefore we calculated the diffuse PAR by coupling several relationships reported in the literature [*Spitters et al.*, 1986; *Reindl et al.*, 1990]. Reindl et al. studied the influence of climatic and geometric variables on the hourly diffuse fraction (visible and near infrared), based on a data set with 22,000 hourly measurements from North American and European locations. They identified four significant predictors: k_t, β, ambient temperature, and relative humidity. Predictive equations were proposed for three sets of predictors: k_t, β, ambient temperature, and relative humidity; k_t and β only; and k_t only. Sensitivity analyses indicate that k_t and β are the two most sensitive variables. Therefore we use k_t and β as the predictors for the diffuse component. The corresponding equations are [*Reindl et al.*, 1990]:

Interval: $0 \le k_t \le 0.3$; Constraint: $S_f/S_e \le k_t$

$$S_f/S_e = k_t[1.020 - 0.254k_t + 0.0123 \sin\beta] \tag{7a}$$

Interval: $0.3 < k_t < 0.78$; Constraint: $0.1k_t \le S_f/S_e \le 0.97k_t$,

$$S_f/S_e = k_t[1.400 - 1.749k_t + 0.177 \sin\beta], \tag{7b}$$

Interval: $k_t \ge 0.78$; Constraint: $S_f/S_e \ge 0.1k_t$

$$S_f/S_e = k_t[0.486k_t - 0.182 \sin\beta], \tag{7c}$$

where S_f denotes the total diffuse radiation (visible plus near infrared) received by a horizontal plane on the Earth surface (W m^{-2}).

To determine the diffuse component in the total PAR (PAR_t, measured), *Spitters et al.* [1986] proposed the following relationship:

$$\mathrm{PAR}_f/\mathrm{PAR}_t = \frac{[1 + 0.3(1 - q^2)]q}{1 + (1 - q^2)\cos^2(90° - \beta)\cos^3\beta}, \tag{8}$$

where PAR_f is the diffuse PAR (μmol photon m^{-2} s^{-1}) and $q = (S_f/S_e)/k_t$. The detailed explanations of (7) and (8) can be found in the work of *Reindl et al.* [1990] and *Spitters et al.* [1986], respectively.

3. Results

For the boreal aspen forest we analyzed measurements over the growing season of 1994. For the temperate mixed forest, measurements of the growing seasons of 1996 and 1997 were analyzed. Since similar results were found for the two years in the mixed temperate forest, only 1997 results are shown for the mixed temperate forest.

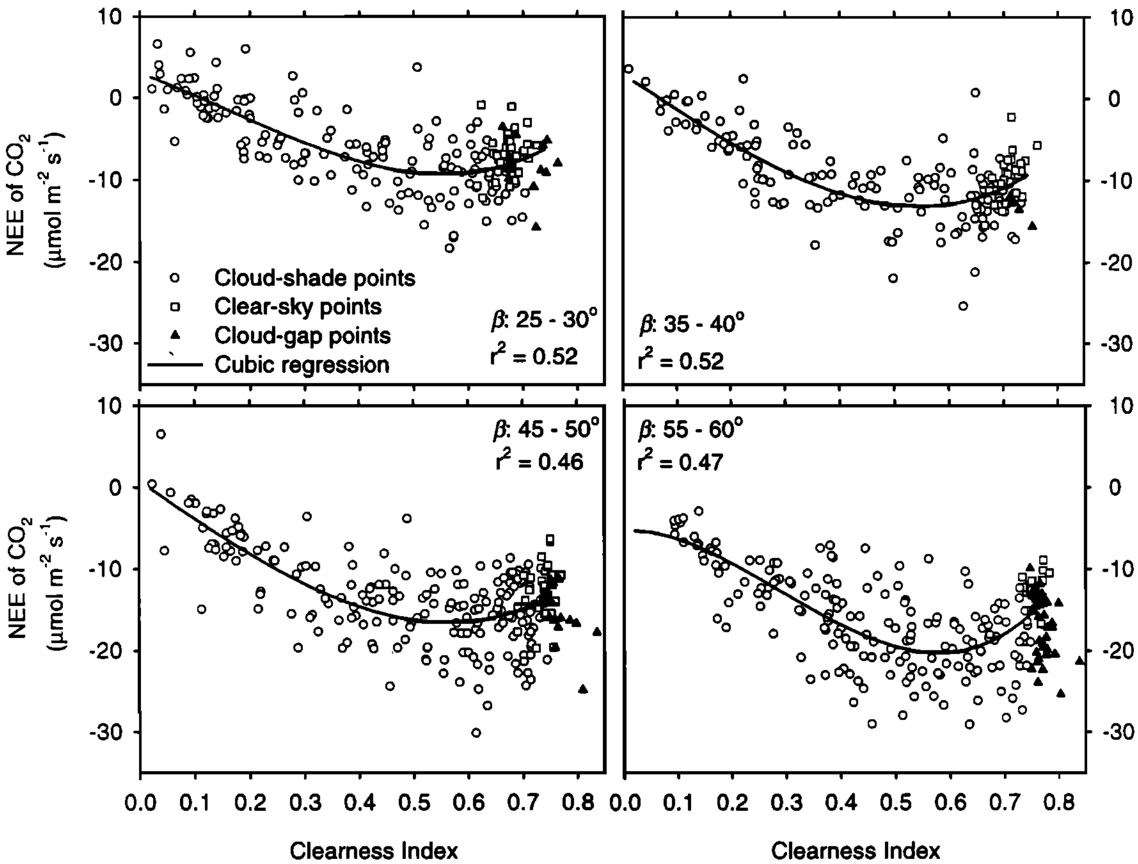

Figure 3. Scatterplots and cubic regressions between the net ecosystem exchange (NEE) of CO_2 and the clearness index for the boreal aspen forest in 1994 for selected 5° intervals of solar elevation angles. Regressions do not include cloud-gap points.

3.1. Changes of NEE With Clearness Index

Results from both the boreal and the temperate sites show that the NEE of CO_2 responds nonlinearly to changes in the clearness index with the maximal NEE occurring at values of the clearness index of intermediately cloudy skies. Figures 3 and 4 show scatterplots and cubic regressions between the NEE and the clearness index for several 5° intervals of solar elevation angles for the boreal aspen forest in 1994 and the temperate mixed forest in 1997, respectively. In the cubic regressions, only measurements from the cloud-shade and clear-sky conditions were included. Measurements from the cloud-gap condition were excluded from the regressions because they follow a different pattern (see the solid triangles in Figures 3 and 4; we will discuss this later). Well-defined nonlinear patterns exist in the relationship between the NEE and the clearness index for each 5° interval of solar elevation angles. The maximal NEE, i.e., most negative value, occurs under cloudy skies (open circles in Figures 3 and 4) with the clearness index generally between 0.4 and 0.6, rather than under clear skies with higher values of the clearness index (open squares in Figures 3 and 4).

The above revealed response of the NEE to the cloud-induced changes in the clearness index is a sharp contrast to the response of the NEE to the solar elevation-induced changes in the clearness index. Figure 5 shows the relationship between the clear-sky NEE and the clearness index for the boreal aspen forest in 1994 (Figure 5a) and the temperate mixed forest in 1997 (Figure 5b). Under clear skies the NEE generally increases with the clearness index. The concave patterns, shown in the response of the NEE to the clouds-induced changes in the clearness index (Figures 3 and 4) do not exist in the relationship between the clear-sky NEE and the clearness index (Figure 5). In fact, the latter clearly shows the opposite-convex patterns (Figure 5). Therefore it can be concluded that the initial increases in the NEE as the sky changes from clear to cloudy shown in Figures 3 and 4 are directly related to the presence of clouds, which in turn may be responsible for or associated with changes in other environmental factors (we will discuss this later).

Because of the cloud-gap effect the highest values of clearness index generally occur under cloudy conditions with patchy skies rather than under clear skies (see solid triangles in Figures 3 and 4). Cloud gaps tend to enhance the NEE as cloud shades do, especially when solar elevation angles are high. This is indicated in Figures 3 and 4 by the general distribution of cloud-gap points in the bottom right-hand corners of the scatterplots.

3.2. Magnitude of NEE Enhancement by Clouds

The baselines for comparisons (the clear-sky NEE, also see (6)) are shown in Figure 6. The relationships between the clear-sky NEE and the sine of solar elevation angles are best described by a third-order polynomial. Because the morning and afternoon clear-sky patterns are slightly asymmetrical, re-

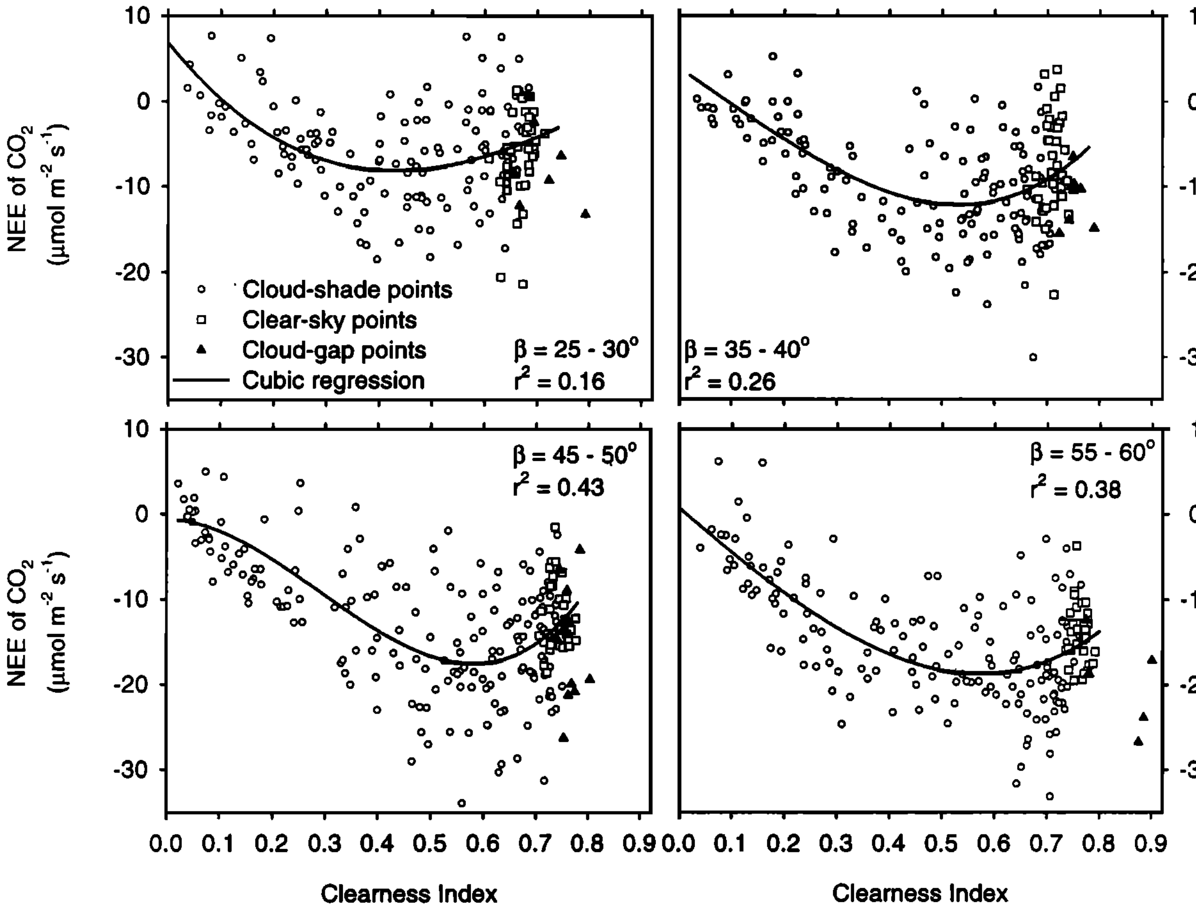

Figure 4. Scatterplots and cubic regressions between the NEE of CO_2 and the clearness index for the temperate mixed forest in 1997 for selected 5° intervals of solar elevation angles. Regressions do not include cloud-gap points.

gressions are done separately for the morning and afternoon. Regressional equations and coefficients are given in Table 2.

Figure 7 shows variations of the 20-point means of changes in the NEE relative to clear skies (%NEE, (6)) with the clearness index for 5° intervals of solar elevation angles. The x coordinates are the medians of values of the clearness index of the corresponding 20 points. For clarity, error bars are shown for only one curve in each plot. Within a fairly large range of the clearness index, the 20-point means of %NEE are significantly larger than zero with $\alpha = 0.05$ (Figure 7). The enhancement of the NEE by clouds changes with solar elevation angles and varies from site to site and year to year. For the boreal aspen forest in 1994 (Figures 7a and 7b) the enhancement at the peak ranged from about 30% for the 20°–25° interval to about 55% for the 55°–60° interval of highest solar elevation angles at this location. For the temperate mixed forest in 1997 (Figures 7c and 7d) the enhancement at the peak ranged from more than 60% for the 30°–35° interval to about 30% for the 65°–70° interval of highest solar elevation angles at the location. The maximal enhancement tends to increase with solar elevation angles for the boreal aspen forest, while the opposite is true for the temperate mixed forest. This highlights the complexity of the relationship between the carbon uptake and cloudiness. The cloud gap effect is demonstrated in the relationships between the 20-point mean %NEE and the clearness index by the reverse trends near the end of the maximal clearness index (Figure 7).

Table 2. Regressional Coefficients of the Cubic Equation $F_c(\beta) = d_0 + d_1 \sin\beta + d_2 \sin^2\beta + d_3 \sin^3\beta$ for Clear Mornings and Afternoons of the Boreal Aspen Forest in 1994 and the Temperate Mixed Forest in 1997

	Regressional Coefficients				
	d_0	d_1	d_2	d_3	r^2
		Aspen Forest, 1994			
Morning	4.89	−22.62	−15.23	19.03	0.81
Afternoon	0.77	−10.82	−22.06	19.43	0.77
		Mixed Forest, 1997			
Morning	4.18	−22.15	−22.43	25.65	0.74
Afternoon	1.47	−19.95	3.54	0.00	0.76

$F_c(\beta)$ is used for the calculation of %NEE through equation (6).

3.3. Optimal and Critical Radiation Environments

To link directly the radiation environment perturbed by clouds with the CO_2 exchange, Figure 8 shows scatterplots and cubic regressions between the NEE and the relative irradiance for the boreal aspen forest in 1994 (Figures 8a and 8c) and the temperate mixed forest in 1997 (Figures 8b and 8d). The non-

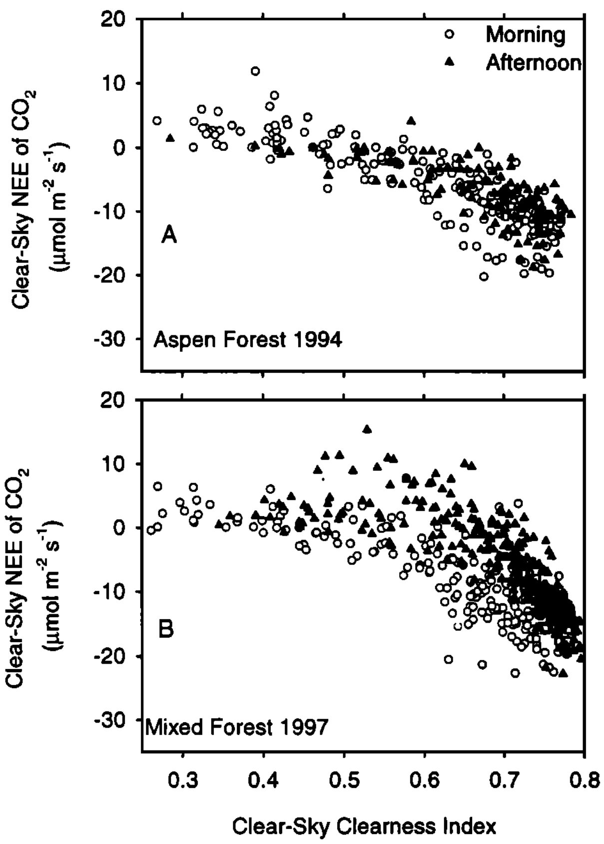

Figure 5. Relationships between the clear-sky NEE of CO_2 and clear-sky clearness index for (a) the boreal aspen forest in 1994 and (b) the temperate mixed forest in 1997.

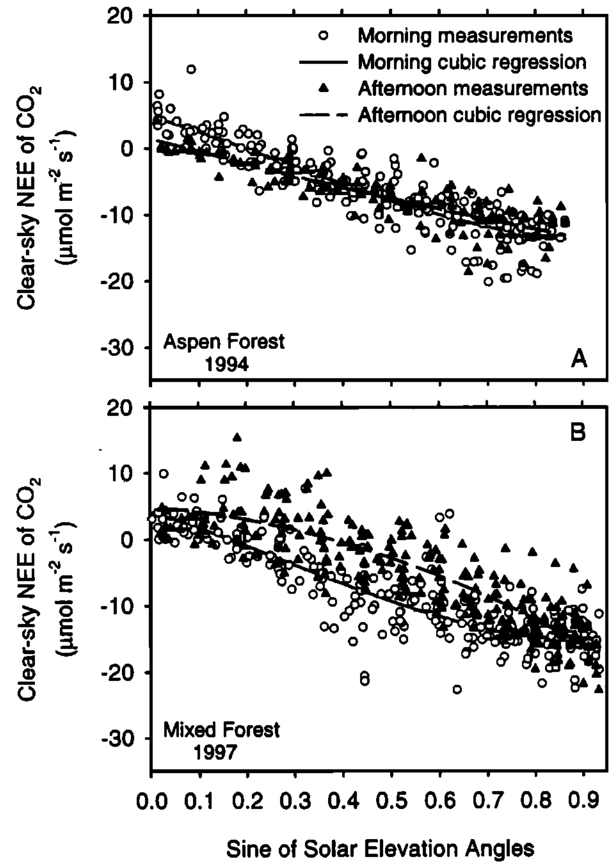

Figure 6. Scatterplots and cubic regressions between the clear-sky NEE of CO_2 and the sine of solar elevation angles for (a) the boreal aspen forest in 1994 and (b) the temperate mixed forest in 1997. The obtained cubic regression equations (given in Table 2) are used to calculate $F_c(\beta)$ in Equation (6).

linear patterns shown in these plots are similar to those shown in Figures 3 and 4 for the clearness index.

From Figures 3, 4, 7, and 8 it is clear that the maximal solar radiation does not result in the maximal NEE. It is interesting to ask the following question: At which irradiance level does a forest ecosystem have the maximal NEE rate? Equally interesting is the question at which irradiance level under a cloudy sky does a forest ecosystem produce the same NEE rate as under a clear sky? We calculated values of the optimal and critical relative irradiances for each 5° interval for these two forests. The optimal relative irradiance for a 5° interval was obtained by solving the corresponding cubic regressional equation for its maximum. The critical relative irradiance for a 5° interval was obtained by solving the corresponding cubic regressional equation for its root at which the NEE equals the clear-sky value (the relative irradiance = 100). Figure 9 shows the optimal and critical relative irradiances against the solar elevation angle at the center of each 5° interval. Both the optimal and the critical relative irradiances vary with solar elevation angles. For the boreal aspen forest in 1994 the optimal (critical) relative irradiance changes from 83% (65%) for the 20°–25° interval to 76% (46%) for the 55°–60° interval (Table 3). For the temperate mixed forest in 1997 the optimal (critical) relative irradiance changes from 75% (54%) for the 20°–25° interval to 67% (36%) for the 65°–70° interval (Table 3). Averaged over solar elevation angles >20°, the optimal and critical relative irradiances are 78 and 53%, respectively, for the boreal aspen forest and 71 and 46%, respectively, for the mixed temperate forest (Table 3). While the aspen forest shows a general trend of decreases in both the optimal and the critical relative irradiances with increases in solar elevation angles, the pattern for the mixed forest is more complex. For high solar elevation angles (>40°) the aspen and mixed forests have close optimal relative irradiances. For low solar elevation

Table 3. Optimal and Critical Relative Irradiances (%) for Every 5° Interval of Solar Elevation Angles >20° at the Boreal Aspen Forest Site in 1994 and the Temperate Mixed Forest Site in 1997

Intervals of β	Aspen Forest in 1994		Mixed Forest in 1997	
	Optimal	Critical	Optimal	Critical
20°–25°	83	65	75	54
25°–30°	81	59	57	34
30°–35°	78	53	70	48
35°–40°	76	49	75	47
40°–45°	78	53	71	48
45°–50°	76	49	78	53
50°–55°	75	50	76	50
55°–60°	76	46	74	47
60°–65°			69	39
65°–70°			67	36
Average	78	53	71	46

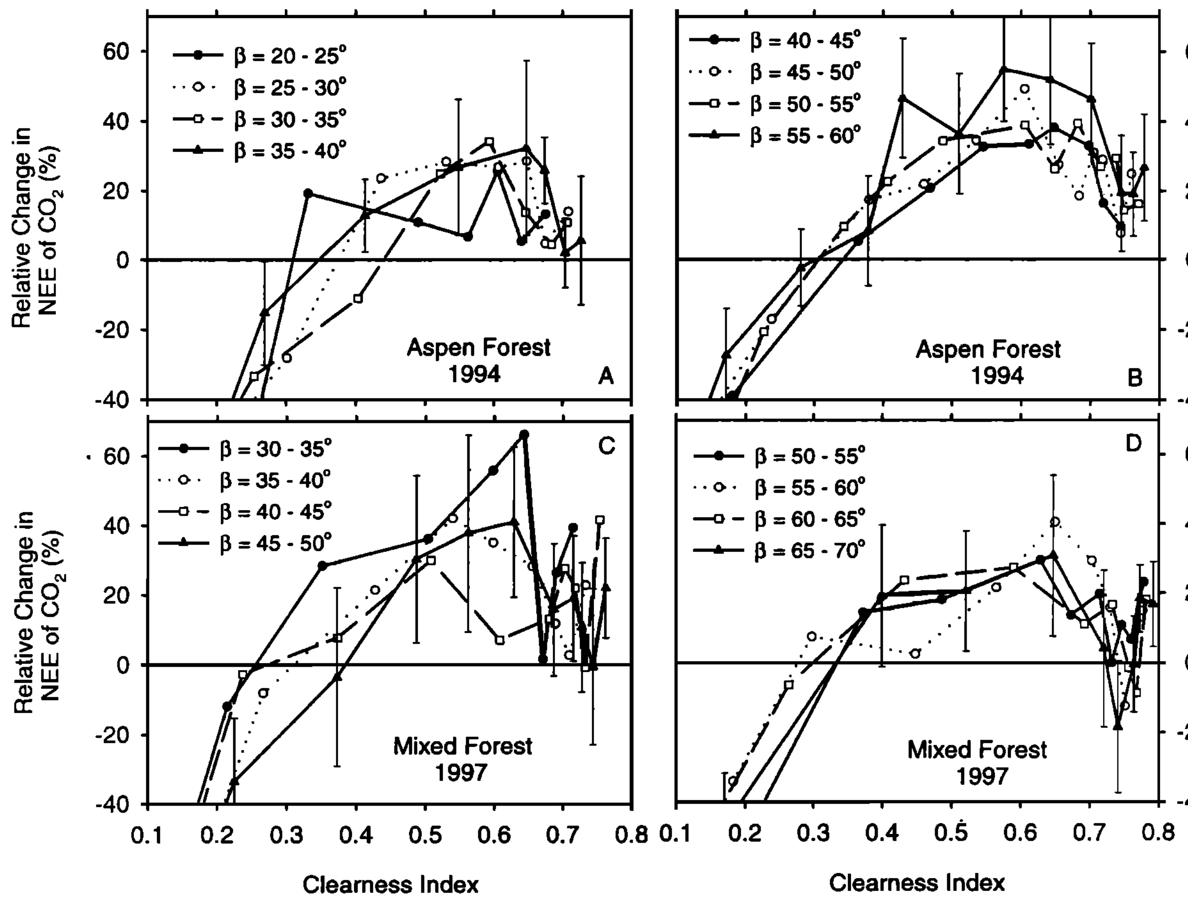

Figure 7. Relationship between the 20-point means of relative changes in the magnitude of NEE of CO_2 relative to clear skies (%NEE) and the clearness index for different intervals of solar elevation angles. The x coordinates are the medians of values of the clearness index of the corresponding 20 points. The error bars represent the 95% confidence interval. For clarity, error bars are shown for only one curve in each plot. (a, b) Boreal aspen forest in 1994. (c, d) Temperate mixed forest in 1997.

angles (<40°) the differences between the two forests are large. The same is true for the critical relative irradiance.

3.4. Potential Environmental Factors Responsible for Enhancement

Previous explanations about the observed enhancement of carbon uptake on cloudy days focused on changes in individual factors. However, the presence of clouds can be both causes and consequences of changes in many atmospheric factors such as solar radiation, temperature, moisture, latent heating, precipitation, etc. These factors all have direct or indirect influences on the biophysical processes controlling exchanges of CO_2 between the forest ecosystems and the overlying atmosphere. Our data from both sites showed that systematic changes in multiple environmental factors that can influence canopy photosynthesis and/or ecosystem respiration tend to coexist when cloudiness varies. In the following we show the results from the boreal aspen forest only. The results from the mixed temperate forest are similar and therefore will not be given here.

Figure 10 shows changes of the measured total PAR and calculated diffuse PAR with the clearness index for the boreal aspen site. Although the total PAR decreases almost linearly as the clearness index decreases (Figure 10a), the relationship between the diffuse PAR and the clearness index is not linear (Figure 10b). As the sky changes from clear to cloudy, the diffuse PAR increases. It reaches its maximum with values of the clearness index in a range of 0.4 to 0.5 (Figure 10b) and then decreases. Because plant canopies have a higher radiation use efficiency for the diffuse PAR than for the direct PAR [*Price and Black*, 1990; *Wang and Jarvis*, 1990; *Gutschick*, 1991; *Hollinger et al.*, 1994; *Rochette et al.*, 1996; *Healey et al.*, 1998; *Gu et al.*, 1999] the gain of canopy photosynthesis due to an increase in the diffuse PAR can exceed the loss due to a decrease in the direct PAR [*Gu et al.*, 1999]. The clearness index at which the maximal diffuse PAR occurs appears to be smaller than the clearness index at which the NEE reaches the maximum (compare Figure 10b with Figures 3 and 4). This is understandable because of the reduced contribution to canopy photosynthesis from the component of direct beam radiation. The increase in the diffuse PAR with the clearness index under sky conditions with high clearness index values is due to the cloud-gap effect (Figure 10b).

Another factor that can enhance canopy photosynthesis is the general trend of decreases in VPD associated with cloudy conditions [*Freedman et al.*, 1998]. Figure 11 shows the relationship between the VPD and the clearness index for 45°–50°

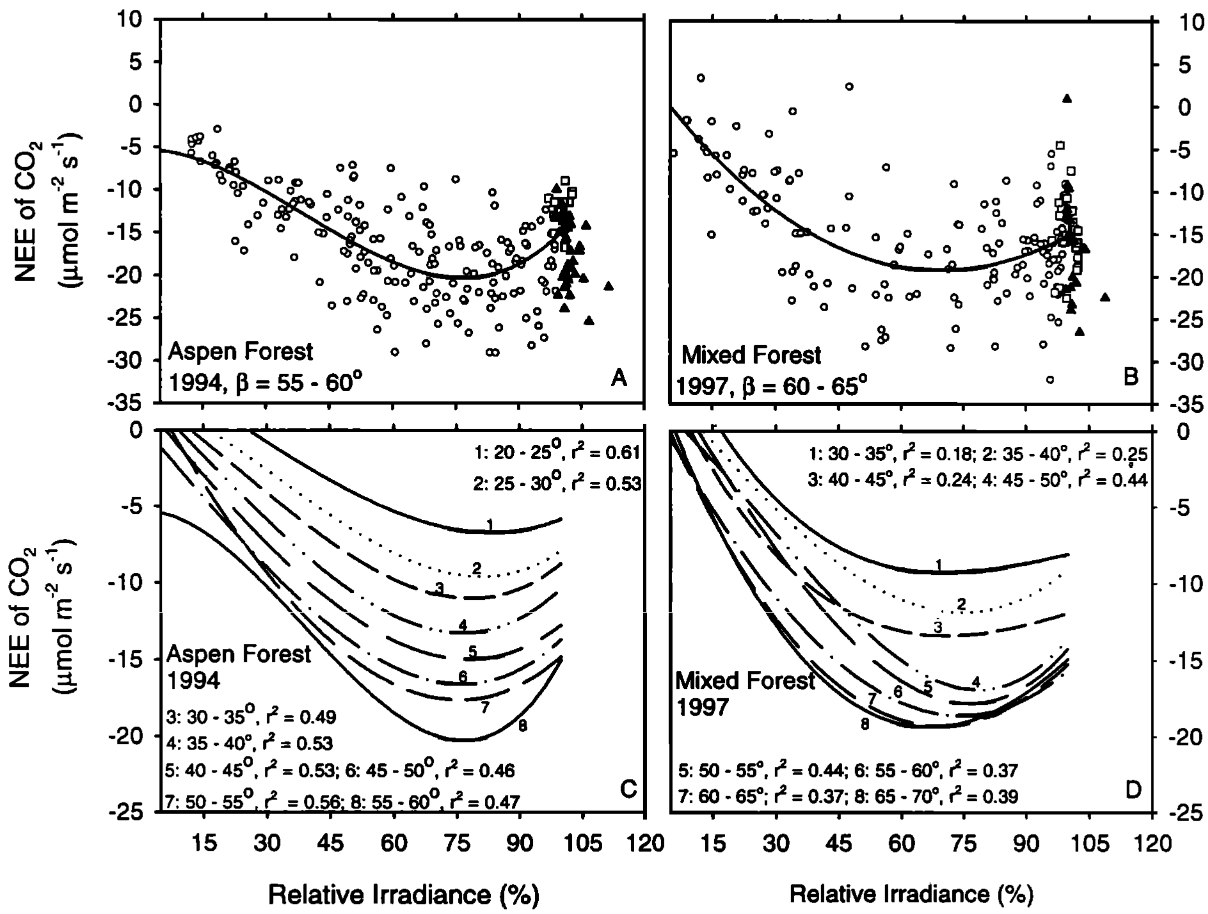

Figure 8. Scatterplots and cubic regressions between the NEE of CO_2 and the relative irradiance for (a, c) the boreal aspen forest in 1994 and (b, d) the temperate mixed forest in 1997. Symbols are the same as in Figures 3 and 4.

and 55°–60° intervals of solar elevation angles. VPD tends to decrease as the clearness index decreases. Similar patterns were also found for other solar elevation intervals (data not shown). The decrease in VPD induces stomatal openness and thus enhances leaf photosynthesis [*Collatz et al.*, 1991].

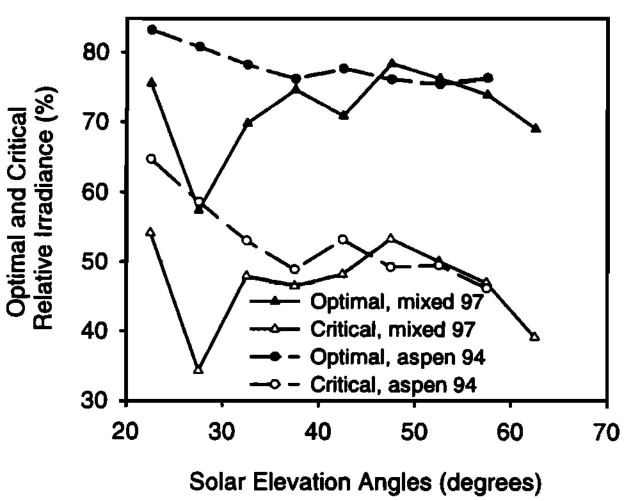

Figure 9. Changes of the optimal and critical relative irradiances with solar elevation angles for the boreal aspen forest in 1994 and the temperate mixed forest in 1997.

The NEE can also be enhanced by decreases in leaf and soil respirations. In general, temperature is the controlling factor in both leaf and soil respiration processes. Figure 12 shows that air and soil temperatures tend to decrease as the clearness index decreases. This is expected because of reduced radiative forcing under cloudy conditions. The decreases in temperatures reduce leaf and soil respirations and thus contribute to the enhancement of net ecosystem carbon uptake under cloudy conditions.

3.5. Do Current Patterns of Cloudiness Allow for Further Increases in Cloudiness to Enhance Carbon Uptake?

Analyses of frequency distributions of values of the clearness index at these two study sites indicate that the current cloudiness patterns still allow for further increases in cloudiness to enhance forest carbon uptake. Figure 13 shows histograms of values of the clearness index in the growing seasons of 1994 in the boreal aspen forest site and of 1997 in the temperate mixed forest site. The histogram for 1996 in the temperate mixed forest site has a similar pattern. The peak of the distribution for both forests is located around 0.75 which is larger than the values of clearness index at which the NEE reaches the maximum (Figures 3 and 4). This indicates that the current patterns of cloudiness at both sites still allow for further increases in cloudiness to enhance carbon uptake.

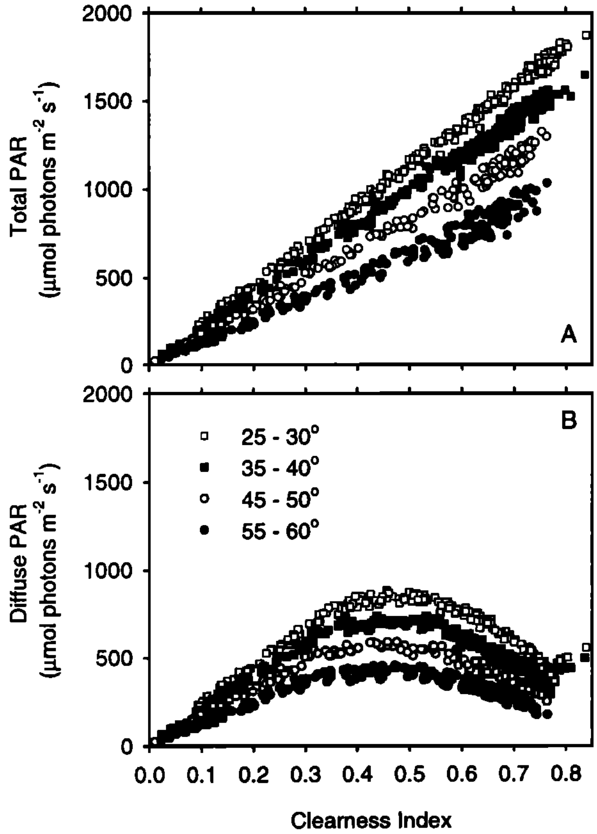

Figure 10. Changes of (a) total photosynthetically active radiation (PAR) and (b) diffuse PAR with the clearness index for different solar elevation angles over the boreal aspen forest in 1994.

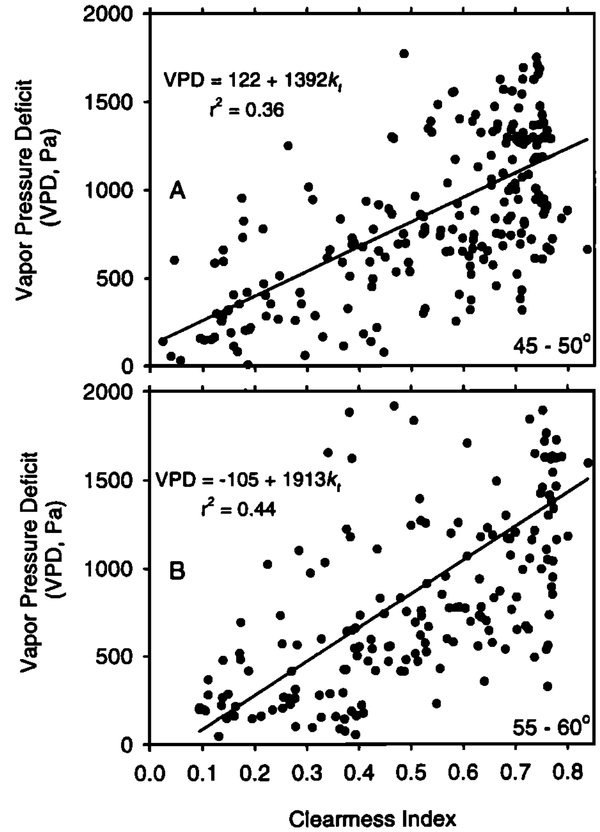

Figure 11. Changes of vapor pressure deficit (VPD) with the clearness index for intervals of solar elevation angles 45°–50° and 55°–60° for the boreal aspen forest in 1994.

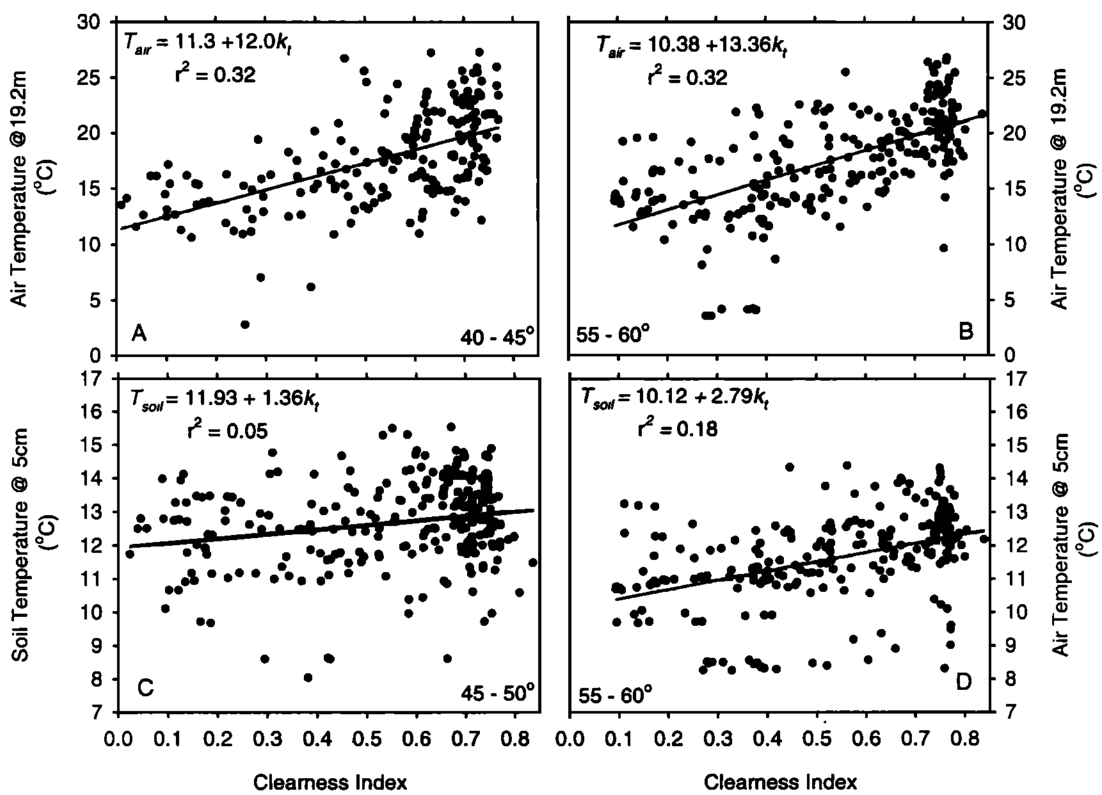

Figure 12. Changes of (a and b) air and (c and d) soil temperatures with the clearness index for selected intervals of solar elevation angles for the boreal aspen forest in 1994. Air temperature was measured at 19.2 m above the ground. Soil temperature was measured at 5 cm below the ground.

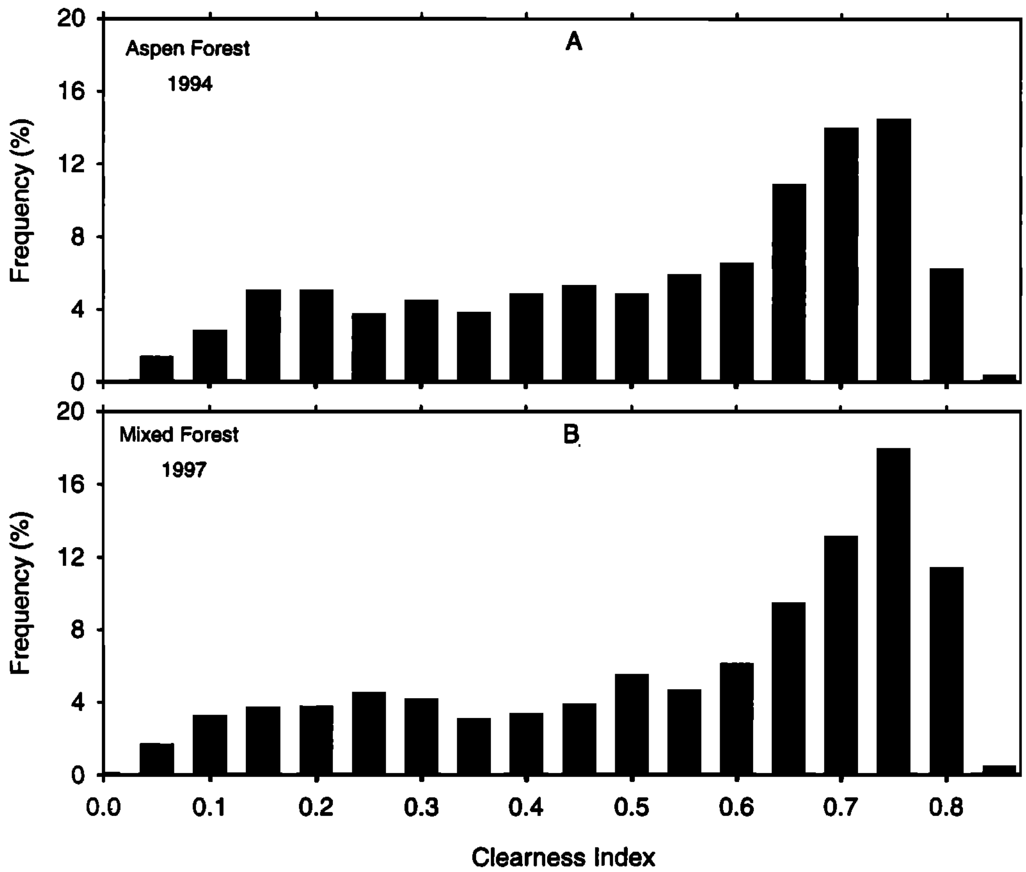

Figure 13. Histograms of values of the clearness index for solar elevation angles >20° at (a) the boreal old aspen site in 1994 and (b) the mixed temperate forest site in 1997.

4. Discussion and Conclusions

In this study, a methodology for the study of the relationship between cloudiness and terrestrial carbon uptake has been developed. The established methodology has been used to quantify the influences of clouds on carbon uptakes by two North American deciduous forests. The enhancement of carbon uptake under the presence of clouds is a consistent phenomenon at both sites. The degree of enhancement depends on cloudiness, solar elevation angles, and forest structure. Although varying with solar elevation angles and differing between the two forests, the maximal enhancement of the NEE by clouds was generally more than 30% at both sites when the clear-sky NEE was used as a baseline for the comparison. The critical and optimal radiation environments for the NEE also depend on solar elevation angles and are slightly different between the two forests. For the boreal aspen forest the optimal and critical relative irradiances averaged over solar elevation angles larger than 20° are 78 and 53%, respectively (Table 3). For the mixed temperate forest these two values are 71 and 46%, respectively (Table 3). These numbers show that for these two forest ecosystems, clear skies do not provide the ideal environmental conditions for the carbon uptake, and cloudiness, which reduces total solar radiation incident on the forest canopy, can actually enhance forest carbon absorption by increasing light use efficiency. They also show that these two forest ecosystems can tolerate exceedingly large reductions of solar radiation due to increases in cloudiness without lowering their capacities in carbon uptake.

Data from both forests showed that as cloudiness increases, many environmental factors could experience systematic changes. We suggest that increases in diffuse radiation, decreases in water stress, air temperature and soil temperature associated with increases in cloudiness all play roles in the enhancement of carbon uptake under cloudy conditions. These factors enhance the carbon uptake by either promoting canopy photosynthesis or reducing leaf and soil respiration.

The major difficulty in the study of influences of clouds on the carbon uptake is the quantitative representation of cloud characteristics and its linkage to real-time flux measurements. Cloud shapes, thickness, size distributions, and spatial distributions are all important properties for radiative transfer and may reflect directly or indirectly other atmospheric regimes, such as temperature, moisture, latent heating, and precipitation. All these aspects can have pronounced influences on exchanges of CO_2 between terrestrial ecosystems and the overlying atmosphere. While other weather elements can be quantified and accurately measured with instrumentation, most cloud properties cannot be easily described by quantitative variables and are best obtained with human eyes [*Duchon and O'Malley*, 1999]. The acquisition of the information on cloud properties and the real-time match with tower-based flux measurements represents a challenge for the future studies of the influences of clouds on terrestrial carbon uptakes.

The general patterns of current sky conditions at both study sites are still too "sunny" for the ecosystem carbon sequestration, and further increases in cloudiness are expected to help these two ecosystems to absorb more CO_2 from the atmosphere. If this pattern is typical in North America, then the past increase in cloudiness over this region [*McGuffie and Henderson-Sellers*, 1988; *Henderson-Sellers*, 1989; *Karl and Steurer*, 1990; *Angell*, 1990] may have contributed to terrestrial ecosystems acting as effective carbon sink, and a continuous trend of increases in cloudiness would promote North American forests to become an even larger carbon sink.

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