Tellus (2003), 55B, 232–243

TELLUS
ISSN 0280–6509

Temporal variations of atmospheric CO_2 concentration in a temperate deciduous forest in central Japan

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(Manuscript received 17 June 2002; in final form 20 December 2002)

ABSTRACT

In order to examine the temporal variation of the atmospheric CO_2 concentration in a temperate deciduous forest, and its relationship with meteorological conditions, continuous measurements of CO_2 and meteorological parameters have been made since 1993 on a tower at Takayama in the central part of Japan. In addition to an average secular increase in atmospheric CO_2 of 1.8 ppm yr^{-1}, diurnal variation with a maximum during the night-time to early morning and a minimum in the afternoon is observed from late spring to early fall; the diurnal cycle is not so clearly observed in the remaining seasons of the year. A concentration difference between above and below the canopy, and its diurnal variation, can also be seen clearly in summer. Daily mean concentration data show a prominent seasonal cycle. The maximum and the minimum of the seasonal cycle occur in April and from mid August to mid September, respectively. Day-to-day changes in the diurnal cycle of CO_2 are highly dependent on the day-to-day variations in meteorological conditions. However, CO_2 variations on longer time scales (>10 d) appear to be linearly related to changes in respiration. At Takayama, variations in the 10-d standard deviation of daily mean CO_2 data and 10-d averaged respiration show distinct relationships with soil temperature during spring and fall seasons. In spring, respiration has a stronger exponential dependence on soil temperature than in fall. Interestingly, in summer when soil temperature becomes greater than about 15 °C, biological respiration becomes more variable and independent of the soil temperature. Thus, at the Takayama site, the Q_{10} relationship is seasonally dependent, and does not represent well the biological respiration process when the soil temperature rises above 15 °C.

1. Introduction

CO_2 is well known as a major greenhouse gas, and the increase in its atmospheric concentration over the last 250 years has started to change global climate (IPCC, 2001). To predict future climate, a better understanding of the global carbon cycle is necessary. Some researchers have shown that the terrestrial biosphere at mid- and high latitudes in the Northern Hemisphere is a very important sink in the global carbon cycle (e.g. Tans et al., 1990; Ciais et al., 1995; Fan et al., 1998; Morimoto et al., 2000). However, large uncertainties still remain in these estimates. Keeling et al. (1996) suggested that, in the Northern Hemisphere, the observed increase in the annual amplitude of the CO_2 seasonal cycle and the phase advance of the downward zero crossing of the seasonal cycle, where decreasing CO_2 crosses the line of the long-term trend, are attributable to the recent observed increases in temperature. However, the impact of climate change on the activity of the terrestrial biosphere is not yet fully understood.

To understand the global carbon cycle better, worldwide systematic measurements of atmospheric CO_2 concentration are being made (GLOBALVIEW-CO_2, 2001). However, most of these stations collect measurements of background air representing global or

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latitudinal CO_2 distribution. To elucidate the role of the terrestrial biosphere in the carbon cycle and to predict the impact of climate change on the CO_2 exchange between the atmosphere and the terrestrial biosphere, systematic measurements are needed at sites influenced directly by terrestrial biospheric activities. However, such measurements are made only at a few sites in the world (Bakwin et al., 1998; Haszpra, 1999; Levin et al., 1995; Inoue and Matsueda, 2001; Higuchi et al., 1999) and are quite insufficient, especially in East Asia, which is largely dominated by the Asian monsoon.

Continuous measurements of CO_2 concentration and meteorological conditions have been made in a temperate deciduous forest in the central part of Japan since September 1993 (Yamamoto et al., 1999). In this paper, results obtained through May 2001 are shown, and temporal variations on different time scales are discussed.

2. Observation

Our observation site is located in a mountainous area in the central part of the main island of Japan (36°08′N, 137°25′E, 1420 m a.s.l.) and is situated about 15 km east of Takayama City (Fig. 1). The main tree species at the site are deciduous broad-leaved trees such as birch and oak, whose average height is about 17 m. The ground surface is covered with bamboo grass. This forest has been protected for at least 40 yr. Budding and defoliation occur in May and October, respectively, and the ground surface is usually covered with snow from December to April. Annual mean temperature is about 7.3 °C and monthly mean temperatures are 20.0 and –4.8 °C in August and January, respectively. Annual precipitation amounts to about 2400 mm on average, and seasonal variation of precipitation shows double peaks in summer and winter. However, the annual precipitation amount and its seasonal dependency show large inter-annual variations. The prevailing winds are southwesterly and northeasterly, reflecting mainly the topographical features around the site. Details of the site can be found in previous papers (Nakazawa et al., 1997b; Yamamoto et al., 1999) and our website (http://www.aist.go.jp/RIODB/PXECO/).

Meteorological instruments and air intakes for the CO_2 concentration measurement are mounted on a 27 m tower. Sample air is collected from four different heights (27, 18, 8.8 and 5.8 m; the last height was moved from 5.8 to 2.0 m in March 1999); the top two levels are above the canopy and the other two are below the canopy. The air is continuously drawn by diaphragm pumps from each height. Water vapor is removed from air samples using an electric dehumidifier, Nafion tubing (Perma Pure Inc.) and a column

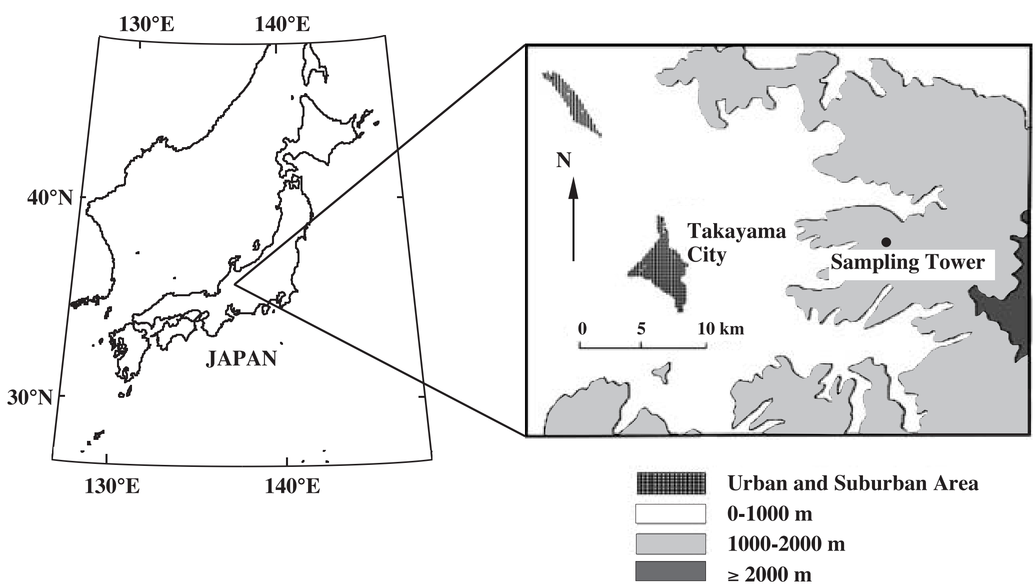

Fig. 1. Map of the observation site.

of magnesium perchlorate. This resulted in a sample dew point lower than −50 °C. Aerosol particles larger than 2 μm are also removed by filters. Air samples are introduced to an NDIR CO_2 analyzer (Beckman model 880 or LI-COR LI-6252). Ultra pure nitrogen (>99.9998%) is fed continuously through the reference cell of the analyzer. The CO_2 concentration at each height is measured twice an hour, and the analyzer is calibrated with air-based working standard gases of four different CO_2 concentrations in the range of about 330–420 ppm, introduced to the analyzer once an hour. These working standards are calibrated against our secondary standards to a precision of 0.01 ppm in our laboratory using an NDIR analyzer (Horiba VIA-500R) before and after usage. A set of the four standard gases was changed with a new set about every 6 months. Changes in the concentration of the working standards associated with their consumption were +0.02 ± 0.03 ppm for 90% of all working standards used in this study, and the maximum drift was +0.14 ppm. The concentrations of the secondary standards are determined against our primary standards produced using a gravimetric method (Nippon Sanso Co., Japan) described in Tanaka et al. (1987). During the observation period, two sets of the secondary standards were used. The old set was used to calibrate the working standards until May 1997 and the new one after that. To track changes in the concentration of the secondary standards, re-calibration by the primary standards and/or examination of internal consistency among the set of the secondary standards described by Matsueda et al. (2002) based on the measurements of the other secondary gases were made at least twice per year. Our secondary standard gases were also calibrated at Tohoku University in 1994 and 1998. From the result of the inter-calibration, the concentration scale based on our primary standards was related to that of Tohoku University, which agrees with the WMO scale to within 0.1 ppm, though it was developed independently (Nakazawa et al., 1997c). Thus, we have employed the CO_2 concentration scale equivalent to that of Tohoku University obtained from the relationship between both concentration scales. With respect to the long-term stability of the relationship between the Tohoku scale and our concentration scale, we examined the difference between the concentrations of the secondary standards calibrated by Tohoku University in 1998 and those estimated from the relationship between the Tohoku scale and our concentration scale determined by the inter-calibration conducted in 1994. The difference for each secondary standard ranged from −0.02 to +0.05 ppm. Also, to estimate the stability, we compared the concentrations for each cylinder evaluated by Tohoku University with those obtained by us using the results of the inter-comparison between Tohoku University, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and our institute conducted in 1995, as well as of the WMO CO_2 round-robin reference gas inter-comparisons held in 1995–1997 and 1999–2000. Note that our institute name was the National Institute for Resources and Environment (NIRE) when these inter-comparison experiments were made. In the Tohoku University–CSIRO–NIRE inter-comparison during 1995 and the 1999–2000 WMO round-robin inter-comparison, differences between the concentration of each cylinder evaluated by Tohoku University and those by NIRE ranged from –0.03 to 0.03 ppm and from 0.00 to 0.04 ppm, respectively. In the 1995–1997 WMO round-robin inter-comparison, agreement was slightly worse and the evaluated values for each cylinder by Tohoku University were higher by 0.08–0.10 ppm than those by NIRE. The reason for this relatively large difference in the 1995–1997 WMO inter-comparison was not clear. However, these results imply that if the concentration scale at Tohoku University is assumed to be stable our concentration scale is also stable to within 0.1 ppm. With regard to the relationship with the WMO scale, our evaluations of the three cylinders in the 1995–1997 and the 1999–2000 WMO inter-comparisons were lower by 0.04–0.11 ppm and by 0.08–0.10 ppm than those by the National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory (NOAA/CMDL), respectively. Based on replicate measurements of the standard gas introduced into the sample line, the overall precision of our measurement system is estimated to be better than 0.1 ppm.

Meteorological parameters are also measured at the tower. Wind speed and direction, temperature and humidity are measured above and below the canopy. Solar radiation is measured near the top of the tower. The outputs of the meteorological instruments and the CO_2 analyzer are stored on a personal computer. The Leaf Area Index (LAI) is estimated from measurements of the transmittance of photosynthetically active photon flux density (PPFD) through the tree canopy (Saigusa et al., 2001). Soil temperature at four different depths is also measured. Precipitation and snow depth are measured at a site located about 1 km from the tower by the Institute for Basin Ecosystem Studies (IBES), Gifu University. At our observation site, fluxes of CO_2, water vapor and sensible heat have also been measured by the eddy covariance method since 1998 (Saigusa et al., 2001; 2002). Takayama is also one of the long-term flux monitoring sites in the AsiaFlux network.

In this paper, hourly data of atmospheric CO_2 and meteorological parameters from Takayama are analyzed. In the analyses, all available data other than the instrumentally false data are used because the CO_2 measurements at Takayama are influenced mostly by local biological sources and sinks. Possible effects of anthropogenic sources on the observed CO_2 at our site in summer were estimated by Kondo et al. (2001) using a numerical model, and were found to be relatively minimal.

3. Results and discussion

In this section, we will present temporal variations of CO_2 on different time scales such as diurnal and seasonal, and discuss their relationships with meteorological conditions and biospheric activities.

3.1. *Diurnal variation*

Figure 2 shows the diurnal variation in CO_2 concentration observed at 27 m height in July 1998 and in January 1998 at Takayama as an example of the typical diurnal variation in summer and winter. The diurnal variation with a maximum during the night or in the early morning and a minimum in the afternoon is clearly observed in summer (Fig. 2a). The daily peak-to-peak amplitude of the variation is sometimes larger than 30 ppm. This diurnal variation is strongly affected by biological activities near the site, i.e., CO_2 uptake by photosynthesis and CO_2 release by plant and soil respiration (decomposition), and variation in height of the mixed layer. As can be seen in this figure, the diurnal amplitude is larger on sunny days when biospheric activities are enhanced than on cloudy days. In the winter, the diurnal variation is hardly observable (Fig. 2b), reflecting weak biological activities, but a small fluctuation with a period of a few to several days appears. This is probably influenced by variation of meteorological conditions on the synoptic scale.

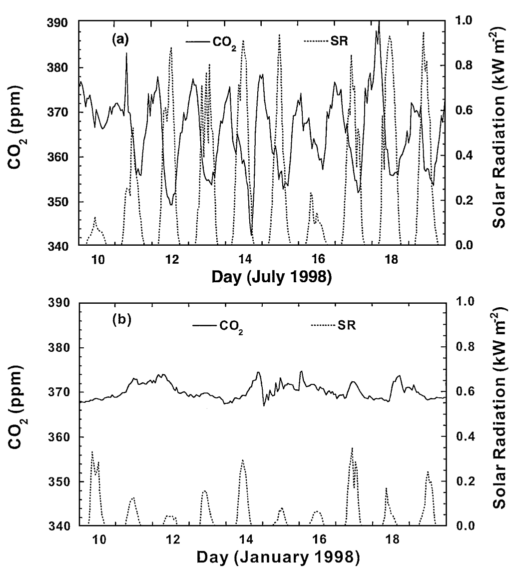

Fig. 2. Diurnal and day-to-day variations of CO_2 concentration and solar radiation in summer (a) and winter (b).

Figure 3 shows average diurnal variations of CO_2 at 27 m height relative to the daily mean on respective (odd) months. In this figure, the plotted value ($\overline{C_{m,h}}$) for the month m and the hour h is calculated as follows;

$$\overline{C_{m,h}} = \sum_i \left(C_{m,i,h} - C_{m,i}^{\text{mean}} \right) \Big/ N_{m,h},$$

where $C_{m,i,h}$ is the hourly mean concentration at the hour h on the day i in the month m of the year, $C_{m,i}^{\text{mean}}$ is the daily mean concentration on the day i in the month m of the year, and $N_{m,h}$ is the number of the data at the hour h in the month m of the year during the whole observed period. It is also found from this figure that a prominent diurnal variation appears from late spring to early fall; the CO_2 concentration starts to decrease rapidly after sunrise, reaches the minimum in the afternoon, rapidly increases after sunset

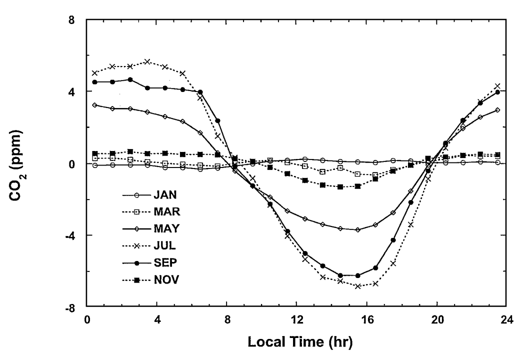

Fig. 3. Mean diurnal variations of the CO_2 concentration at the 27 m height relative to the daily mean for each month over the whole observed period.

and reaches the maximum at midnight. On the other hand, the monthly averaged diurnal cycle vanishes in the winter. In November, a small diurnal variation with the minimum in the afternoon appears. Figure 4 shows average diurnal variation of the vertical profile of the concentration relative to 27 m every 3 h in each season. Each plotted value is obtained by averaging the relative concentration at the selected height to 27 m at the selected hour of the day for each month of the year over the observed period. In this figure, the values at 27 m for each profile are shifted by 1 ppm relative to the previous profile. The values for 27, 18 and 8.8 m are averaged for the whole observed period, but those for 5.8 and 2.0 m are averaged for the period before and after March 1999, respectively. In January, the height-dependent difference of CO_2 is very small throughout the day, reflecting reduced biological activities in the winter. The concentration is slightly higher at 2.0 m than at other heights. In April, the vertical difference is still small throughout the day, with CO_2 being slightly higher near the surface than at any other heights in the night-time; however, in the daytime, the gradient is reversed. In July, the vertical CO_2 difference is enhanced and its diurnal variation is large. In the night-time, the concentration increases with deceasing height and the vertical gradient is steep near the surface. The vertical difference between 2.0 and 27 m becomes greater than 8 ppm. On the other hand, CO_2 decreases with decreasing height above 8.8 m and increases toward the ground surface below 8.8 m in the daytime. The October profiles are similar to those observed in July, but with smaller vertical differences.

The small diurnal variation and the small vertical difference in winter and in early spring reflect reduced biological activities near the site during these seasons. The slightly higher CO_2 concentration observed near the surface may be caused by soil respiration through the snow. In this context, it is interesting to note that Yamamoto et al. (1999) found, through flux measurements, a small net release of CO_2 from the forest to the atmosphere at this site during the biologically less active seasons. Also, Mariko et al. (2000) confirmed a small CO_2 flux from the snow surface to the atmosphere at the site in the wintertime using different measuring methods. As described above, during the daytime in April, the concentration is slightly lower at 2.0 m than at heights above. At this time of the year, the budding of trees has not yet started. However, leaves of the bamboo grass can start photosynthetic activities after they are free of melting snow, since sunlight readily reaches the ground surface due to the lack of tree leaves. Furthermore, CO_2 emission from the ground due to soil respiration is small because of low temperatures at this time of the year. Therefore, the concentration is decreased more near the ground than at higher levels. Similar processes operate in November when trees are defoliated but before any significant snow accumulation takes place at the ground. The diurnal variation is small (Fig. 3) and the vertical profiles (not shown) are similar to those observed in April.

The large diurnal CO_2 variation and the large variability of the vertical profile of CO_2 observed at Takayama in the summer are mainly due to (1) enhanced biological activities (photosynthesis and respiration) and (2) diurnal variation of mixed layer height near the surface in this season. The concentration is higher near the ground surface than above all day long, reflecting enhanced soil respiration due to higher temperatures in this season. This may also be related to reduction of CO_2 uptake near the ground surface in this season due to suppression of incident sunlight to the lower layer by dense tree leaves. The decrease of CO_2 from sunrise to afternoon (Fig. 3) and the lowest CO_2 seen at 8.8 m in daytime (Fig. 4) are attributed to CO_2 uptake by enhanced photosynthesis activity. Reduction of the vertical CO_2 difference in the daytime is caused by enhanced vertical mixing of air. After sunset, photosynthesis stops, and the CO_2 emitted by soil and plant respiration accumulates near the surface due to rapid stratification of the atmosphere near the surface. As a result, the CO_2 concentration increases rapidly in the surface layer. In this connection, temperature inversion with height is often observed between 25.5 and 9.0 m at the tower from sunset to sunrise.

Compared with results for similar heights at the Wisconsin tower by Bakwin et al. (1998) and at the towers in Hungarian rural areas by Haszpra (1999), the observed amplitude of the diurnal variation is smaller at Takayama in summer. This can probably be attributed to different vegetation and climate at each location. Furthermore, easterly down-slope wind sometimes blows from the mountain to the valley at our site in the night-time. This wind could transport CO_2-depleted air less influenced by biological respiration from upper atmospheric layers to the observation site. This could suppress the increase of the concentration in the night-time and result in smaller diurnal amplitude. In fact, the CO_2 increase is suppressed from midnight to sunrise at our site (Fig. 3) while the concentration continues to increase at the Wisconsin tower and the Hungarian towers throughout the night-time. In the fall, biological activities are reduced, and as a

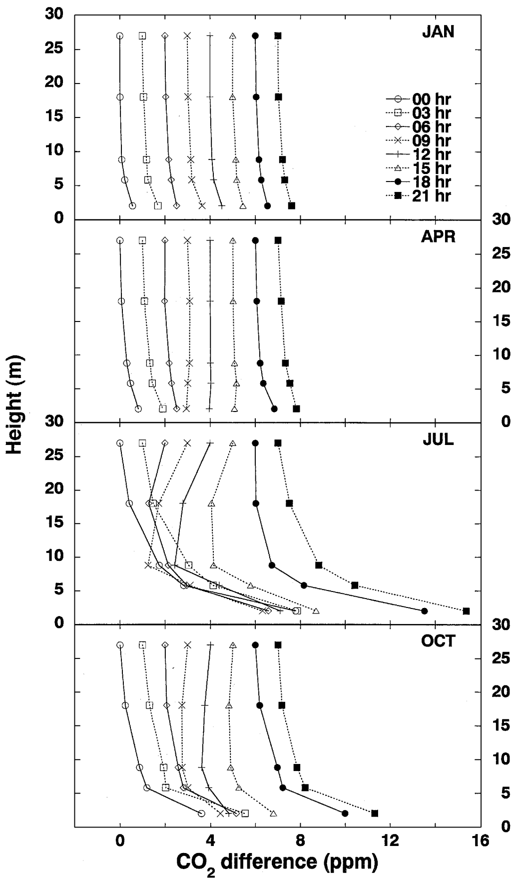

Fig. 4. Mean diurnal variations of the relative vertical profile of the concentration to 27 m every 3 h in each month. The plotted values at 27 m for each profile are shifted by 1 ppm relative to the previous profile. The values for 27, 18 and 8.8 m are averaged for the whole observed period, but those for 5.8 and 2.0 m are averaged for the period before and after March 1999, respectively.

result, diurnal variations and the vertical differences are reduced compared to summer.

3.2. *Seasonal cycle*

In order to obtain the seasonal cycle and the secular trend from the observed CO_2 data, we employed the curve-fitting technique described in Nakazawa et al. (1997a). In this iterative procedure, the fundamental and its first and second harmonics (a 3-harmonic fit) are used. In Fig. 5, daily averaged CO_2 data at the 27 m height, the best fit curve to these data and the secular trend are shown. The daily averaged data are calculated using hourly mean data all day long. Here, the results for 27 m are shown, so as to compare them with the results of the net ecosystem exchange (NEE) measurement at 25 m as described below and to see representative CO_2 variations of a wide area in this forest. From this figure, it is found that the daily data show a prominent seasonal cycle indicating biological activities, though the data are scattered, especially in summer. The maximum and the minimum of the cycle occur in April and from mid-August to mid-September, respectively. Average peak-to-peak amplitude over the observation period obtained from the fitted curve is about 9 ppm. From the secular trend shown in Fig. 5, it is found that the average rate of increase during the period is about 1.8 ppm yr^{-1}, which is close to the recent rate of increase observed at background CO_2 monitoring stations (IPCC, 2001). The secular increase shows inter-annual variation with a larger increase rate in 1998 than in other years during the observed period. In this connection, the high rate of CO_2 increase associated with the 1998 ENSO event was also observed at many background monitoring stations (IPCC, 2001), and higher-than-normal temperatures were recorded in the tropics and Northern Hemisphere extratropics during 1998 (Bell et al., 1999). The high CO_2 increase rate observed at Takayama in 1998 may be related to these factors.

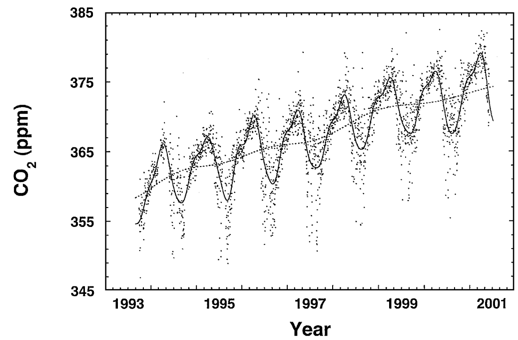

Fig. 5. Daily mean CO_2 concentration calculated from 24-h data (all-day data) at the 27 m height (dots), a best-fit curve to the data (solid line) and a secular trend (dashed line). The standard deviation of the data from the fitted curve is 2.8 ppm.

In Fig. 6 the best-fit curve for the 27 m averaged daily data from the Takayama site is compared with those for (1) the Takayama 27 m daytime-averaged data (daytime data) calculated from the hourly mean data between 1100 and 1700 local time, when the

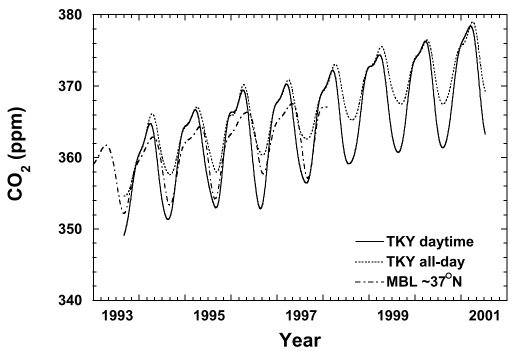

Fig. 6. Best-fit curves of the CO_2 concentration to the daytime (solid line) and the all-day data (dashed line) at 27 m height at the Takayama site, and the reference marine boundary layer average data at about 37°N (dash-dot line).

concentration is relatively stable and vertical mixing of air is enhanced, and (2) reference marine boundary layer (MBL) data at 37°N obtained from GLOBALVIEW-CO_2 (2001). The differences among the three CO_2 seasonal cycle curves show the degree of impact that the seasonality in biological processes of the local ecosystem dynamics can have on the Takayama CO_2 concentration measurements. The details of the causal connection between the CO_2 flux and the resultant atmospheric CO_2 concentration are complicated; however, the following salient features can be noted in Fig. 6:

(1) *Comparison between the all-day and daytime averaged measurements at Takayama:* Comparison shows that they are comparable in concentration level during the winter; but in the summer growing season, the daytime averaged concentrations are considerably lower. This reflects the correlation of diurnal development of the planetary boundary layer and the diurnal cycling of CO_2 respiration and photosynthesis, resulting in the strong weighting of the night-time respiration signal in the all-day averaged data. Average seasonal amplitude for the daytime averaged data is about 6 ppm larger than that for the all-day averaged data. This difference in the seasonal cycle produces, on average, a higher concentration of about 2.8 ppm for the all-day averaged CO_2, compared to the daytime averaged CO_2. It is interesting to note also that, from early to mid-spring, not only is the all-day averaged CO_2 slightly higher than the daytime averaged CO_2, its seasonal decrease begins, on average, about 2 wk after the start of the seasonal decrease for the daytime averaged CO_2. This difference results from the fact that the all-day averaged CO_2 is less affected by the beginning of the daytime photosynthesis of the bamboo grass after the spring snowmelt than the daytime averaged CO_2.

(2) *Comparison with the MBL data:* The data for the MBL at 37°N are reflective of the "background" atmospheric CO_2 concentrations at the latitude where the Takayama site is located. Being removed from and less influenced directly by local biological activities, the MBL seasonal cycle shows clear differences from those observed at Takayama. During the warm growing season, the MBL concentrations are slightly higher (with the exception of 1996 when they are significantly higher) than the daytime averaged data from Takayama; they are considerably lower compared to the all-day averaged observation at Takayama. During the cold season, the MBL concentrations are typically about 3 ppm lower than those (both daytime and all-day) measured at Takayama. The MBL peak concentration and the spring decrease occur about 1 month later than the Takayama daytime averaged data. The average amplitude of the MBL seasonal cycle is about 5 ppm smaller than that for the Takayama daytime averaged data. These facts show that the Takayama site is much more influenced by seasonal change of biological activities compared to the MBL. Compared with the average seasonal amplitude for the Takayama all-day data, the average amplitude at the MBL is larger by 0.7 ppm. This is attributed to the fact that the Takayama all-day data reflect the strong weighting of the night-time respiration as described above. The overall MBL concentration averaged over the 1994–1997 period is lower by 2.5 ppm when compared to the all-day averaged data, but similar to (higher by 0.1 ppm than) the daytime averaged data at Takayama.

3.3. *Seasonal change of CO_2 variability*

In Section 3.1 we have already discussed the CO_2 concentration variability on a diurnal time scale. However, the CO_2 concentration time series also show variability changing over longer time scales (>10 d). In Fig. 7 residuals of the daily all-day data at 27 m height from the best-fit curve shown in Fig. 5 are plotted. It is clearly seen from this figure that the variability in concentration is larger in spring and summer and lower in fall and winter. The deviations sometimes exceed 10 ppm. This is a reflection of the influence of the local biospheric sources and sinks, since such large variability during the growing season is not apparent at background CO_2 concentration monitoring stations.

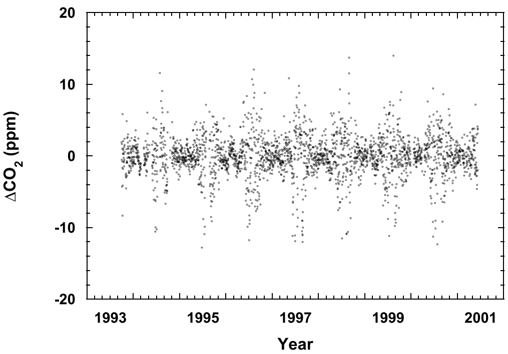

Fig. 7. Deviation of the daily (all-day) data at 27 m height from the best-fit curve shown in Fig. 5.

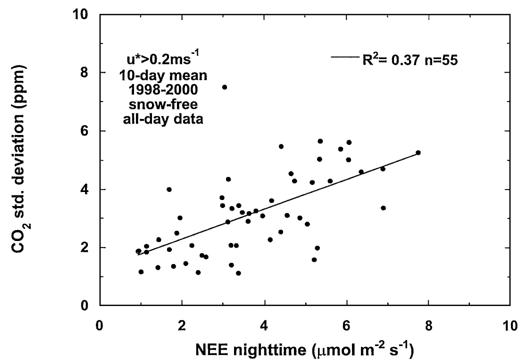

Fig. 8. Relationship between standard deviation of the daily CO_2 (all-day) data at 27 m height from the best-fit curve and 10-d average night-time net ecosystem exchange of CO_2 (NEE) in 1998–2000 under snow-free conditions. Only NEE data under the condition of friction velocity $u^* > 0.2$ m s^{-1} are used. R^2 and n shown in this figure are the square of the correlation coefficient and the number of data, respectively.

Similar variability features are evident at other continental sites (e.g. Bakwin et al., 1998; Higuchi et al., 1999). Near-surface CO_2 concentration variability is governed by the interaction of boundary layer dynamics and CO_2 sources and sinks. Since boundary layer dynamics (particularly boundary layer height) have a power spectrum with a maximum on a diurnal time scale, the role of sources and sinks over a longer time scale (>10 d) may become important.

Next we examine the relationship of growing-season CO_2 variability to the local biospheric sources and sinks. To represent the 10-d time scale variability in the CO_2 concentration, using the difference of the daily all-day CO_2 data at the 27 m height from the best-fit curve (data from Fig. 7), we computed the standard deviation for every 10 d under snow-free conditions. Then we examined the relationship of these computed standard deviations to the local biospheric respiration. For respiration data, we used the measured NEE of CO_2 in the night-time at our site. The NEE data are 30-min average values measured by using an eddy covariance method described in Saigusa et al. (2001), and the NEE measurement by this method has been made at Takayama since the summer of 1998. Here, we used only the night-time NEE data under the condition of friction velocity $u^* > 0.2$ m s^{-1} to avoid significant influences caused by the CO_2 storage in the canopy and other methodological problems, which often occurred on calm stable nights (Saigusa et al., 2001). Therefore, the obtained NEE is almost equivalent to the CO_2 release by respiration and decomposition. The NEE data thus selected are averaged every 10 d under snow-free conditions.

Figure 8 shows the relationship of 10-d CO_2 concentration standard deviation and 10-d averaged night-time NEE in 1998–2000 (the period for which we have eddy covariance data available). There is a statistically significant correlation between CO_2 variability and night-time NEE at the 95% confidence level ($R^2 = 0.37$, $n = 55$, where R is the correlation coefficient and n is the number of data).

Similar analysis (not shown) applied to the 10-d CO_2 concentration standard deviation and 10-d averaged daytime NEE during the period when leaves of deciduous trees exist showed no significant relationship ($R^2 = 0.10$, $n = 38$). Since daytime NEE is representative of the sum of photosynthesis and respiration, we also examined the relationship of CO_2 variability and 10-d averaged solar radiation (sometimes used as a proxy for photosynthesis). Again no significant relationship was evident ($R^2 = 0.02$, $n = 47$). Thus, photosynthesis, as represented by daytime NEE or solar radiation, does not significantly influence the CO_2 variability over a time scale longer than 10 d.

Since the CO_2 variability is closely related to respiration, we also examined the relationship of the CO_2 variability and NEE to soil temperature. Figure 9 shows the time series of CO_2 variability, night-time NEE and 10-d averaged soil temperature at 10-cm depth at our site for the period 1998–2000. Correlations can be separated into three categories: (1) in spring (April–July) there is a strong increase of CO_2 variability and NEE with soil temperature increase; (2) in summer, when soil temperature exceeds 15 °C, CO_2 variability and NEE appear to be independent of soil

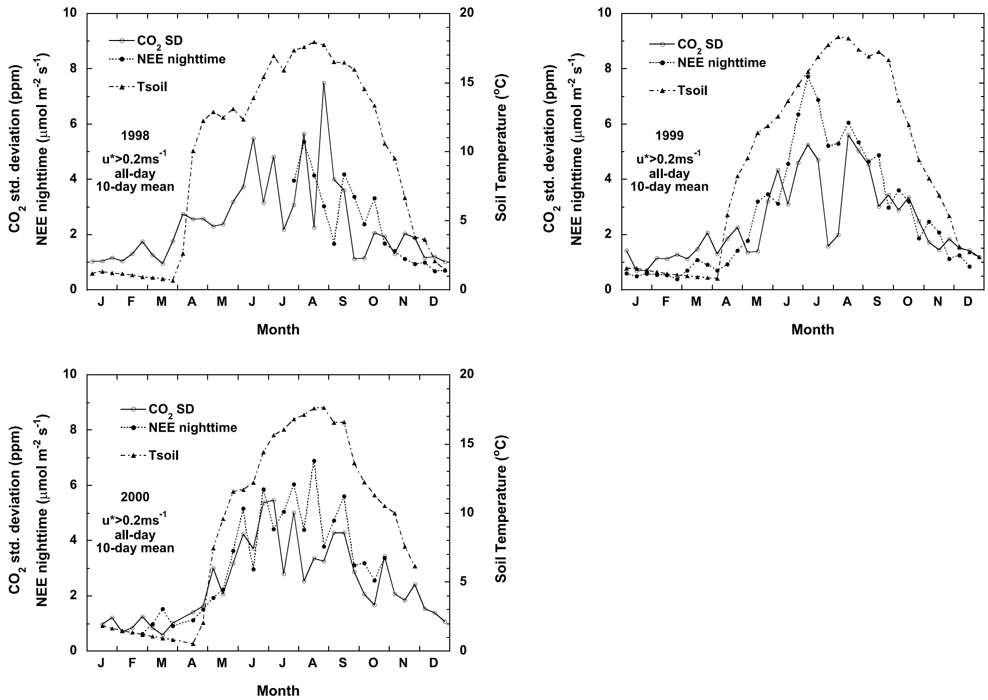

Fig. 9. Temporal variations in the standard deviation of the daily CO_2 (all-day) data (CO_2 SD) at 27 m height from the best-fit curve for every 10 d, the 10 d average night-time net ecosystem exchange of CO_2 (NEE) and average of soil temperatures (Tsoil) at 10 cm depth every 10 d for each year from 1998 to 2000. Only NEE data under the condition of friction velocity $u^* > 0.2$ m s^{-1} are used.

temperature, and there is significant additional variability observed in both CO_2 variability and NEE that is not reflected in soil temperatures; (3) in fall (August–December) CO_2 variability and NEE decrease with decreasing temperature, but the decrease of the variability is more gradual compared to its increase in the spring. This suggests that there is a different functional dependence of respiration on soil temperature.

Figure 10a shows the relationship between 10-d averaged nighttime NEE and the average of soil temperatures at 10-cm depth every 10 d in 1998–2000 under snow-free conditions. Data for April–July and those for August–December are plotted using different symbols in this figure. From this figure, it is seen that NEE increases with increasing soil temperature although the data are somewhat scattered, especially for soil temperatures higher than 15 °C, where nighttime NEE appears to be only weakly dependent on soil temperature as mentioned above. In this figure, fitting curves to the data for each period using exponential functions are also shown. From comparison between the fitted curves, spring to summer night-time NEE increases more rapidly with soil temperature than from summer to fall. Figure 10b shows the same data as in Fig. 10a but excluding the NEE data associated with soil temperature higher than 15 °C. The different temperature dependency of night-time NEE between each season is seen more clearly in Fig. 10b. Student's *t*-test shows that the growth rate difference between spring and fall is significant at the 95% confidence level. Similar relationships (not shown) are evident in the functional dependence of the CO_2 standard deviation on soil temperature.

From these results, it appears that the CO_2 variability largely reflects biological respiration and decomposition activities. We suggest that the usual parameterization of soil respiration as a single exponential function of temperature (i.e., a Q_{10}-type function) may not be sufficient. For our site at least, biological respiration appears to have a very different exponential functional dependence on soil temperature in the spring and fall, and possibly another type of relationship in mid-summer. The difference in temperature dependency of biological respiration and

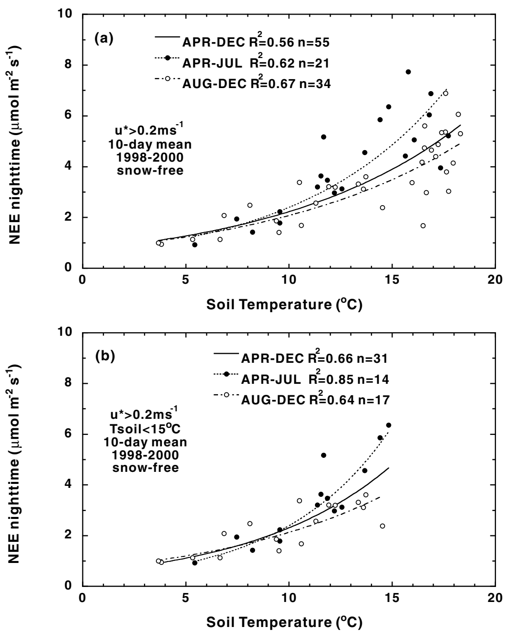

Fig. 10. Relationship between the 10-d mean night-time net ecosystem exchange of CO_2 (NEE) and average of soil temperatures at 10 cm depth every 10 d during 1998–2000 under the condition with no-snow cover (a); same as (a) but for lower soil temperature than 15°C (b). Only NEE data under the condition of friction velocity $u^* > 0.2$ m s^{-1} are used. R^2 and n shown in this figure are the square of the correlation coefficient and the number of data, respectively.

decomposition activities between different seasons may imply an influence of factors other than temperature on these biological activities. In this connection, representation of the relationship between soil respiration and temperature by different type functions from an exponential function has been suggested, and performance of these functions has been examined (e.g. Lloyd and Taylor, 1994; Buchmann, 2000; Fang and Moncrieff, 2001). Some researchers have also proposed models of soil respiration taking into account the effects of soil temperature, soil moisture content and rainfall (e.g. Raich and Schlesinger, 1992; Davidson et al. 1998; Lee et al., 2002; Rey et al., 2002; Raich et al., 2002). The different factors affecting respiration are under investigation at this site.

4. Conclusion

To elucidate diurnal, seasonal and inter-annual variations of CO_2 concentration in a temperate deciduous forest in Eastern Asia and to understand factors governing their variations, continuous measurements of the concentration and meteorological parameters have been made on a tower in central Japan from 1993 to the present. The results obtained from the measurements are as follows:

1. Diurnal variations of CO_2 concentration, with a maximum during the night-time to early morning and a minimum in the afternoon, were seen from late spring to early fall, while it was not clearly observed in winter. Vertical CO_2 profiles in and above the forest also showed a clear diurnal variation in summer. Day-to-day changes in the diurnal variation were highly dependent on the day-to-day variation in meteorological conditions, in particular solar radiation.

2. Daily mean concentration showed a prominent seasonal cycle with a maximum in April and a minimum from mid-August to mid-September, a result of the seasonal change in biological activities. Average amplitude of the seasonal cycle obtained from the all-day averaged data was about 9 ppm, about 6 ppm smaller than the average amplitude obtained from the daytime-only averaged data. This reflects the correlation of diurnal development of the planetary boundary layer and the diurnal cycling of CO_2 respiration and photosynthesis, resulting in the strong weighting of the night-time respiration signal in the all day averaged data.

3. A secular increase in the concentration was observed. The average increase in rate over the observation period was 1.8 ppm yr^{-1}. Its inter-annual variation was also seen to have a high increase in rate in 1998.

4. CO_2 respiration dependence on soil temperature varies with season, which is reflected in the CO_2 concentration variations on longer time scales (>10 d). Respiration in the spring has a stronger exponential dependence on soil temperature than in the fall. In the summer, respiration appears to be independent of soil temperature. These results suggest that a single exponential or Q_{10}-type functional relationship of biological respiration to soil temperature does not appear to be an adequate representation of biological respiration processes over the entire growing season, at least at the Takayama site. Other factors, such as soil moisture content and rainfall, may be important at this site. These results may have implications on ecosystem models and carbon cycle studies.

The results obtained in this study are certainly useful for verifying and improving carbon cycle and biological models, especially in the Asian monsoon region where systematic observations are very sparse. In particular, different relationships of the biological respiration with soil temperature for different seasons obtained in this study can provide a constraint on the biogeochemical carbon cycle models. They can also prove helpful in estimating the response of the carbon cycle to global climate change. For a more definite interpretation of CO_2 variability in a forest on different temporal and spatial scales, further long-term measurements are needed. Comparisons with data for isotopes of CO_2 and water and biological factors should be useful. For a quantitative discussion, analyses using carbon cycle models on local to regional scales are also necessary.

5. Acknowledgments

We thank all the members of the Institute for Basin Ecosystem Studies, Gifu University for their cooperation. We are very grateful to Mr. Katsuhiko Muto (National Institute of Advanced Industrial Science and Technology, Japan) for his support for our measurements. We also thank Dr. Kaz Higuchi (Meteorological Service of Canada, Canada) for his helpful discussions and suggestions and Dr. Wen-Hong Mo (University of Tsukuba, Japan) for her useful comments on soil respiration. Mr. Akihiro Kudo (Japan ANS Co. Ltd., Japan) largely contributed to improvement of our measurements. This study was supported financially by the Global Environment Research Fund of the Japanese Ministry of the Environment.

REFERENCES

Bakwin, P. S., Tans, P. P., Hurst, D. F. and Zhao, C. 1998. Measurements of carbon dioxide on very tall towers: results of the NOAA/CMDL program. *Tellus* **50B**, 401–415.

Bell, G. D., Halpert, M. S., Ropelewski, C. F., Kousky, V. E., Douglas, A. V., Schnell, R. C. and Gelman, M. E. 1999. Climate assessment for 1998. *Bull. Am. Meteorol. Soc*. **80**, S1–S48.

Buchmann, N. 2000. Biotic and abiotic factors controlling soil respiration rates in *Picea abies* stands. *Soil Biol. Biochem*. **32**, 1625–1635.

Ciais, P., Tans, P. P., Trolier, M., White, J. W. C. and Francey, R. J. 1995. A large northern hemisphere terrestrial CO_2 sink indicated by the $^{13}C/^{12}C$ ratio of atmospheric CO_2. *Science* **269**, 1098–1102.

Davidson, E. A., Belk, E. and Boone, R. D. 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. *Global Change Biol*. **4**, 217–227.

Fan, S.-M., Gloor, M., Mahlman, J., Pacala, S., Sarmiento, J., Takahashi, T. and Tans, P. 1998. A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models. *Science* **282**, 442–446.

Fang, C. and Moncrieff, J. B. 2001. The dependence of soil CO_2 efflux on temperature. *Soil Biol. Biochem*. **33**, 155–165.

GLOBALVIEW-CO_2. 2001. Cooperative Atmospheric Data Integration Project - Carbon Dioxide. CD-ROM, NOAA/CMDL, Boulder, Colorado. (Also available on Internet via anonymous FTP to ftp.cmdl.noaa.gov, Path: ccg/co2/GLOBALVIEW).

Haszpra, L. 1999. On the representativeness of carbon dioxide measurements. *J. Geophys. Res*. **104**, 26 953–26 960.

Higuchi, K., Trivett, N. B. A., Shashkov, A., Leeder, L. and Ernst, D. 1999. In situ CO_2 measurements. In: *Canadian Baseline Program Summary of Progress to 1998*. Atmospheric Environment Service, Environment Canada, Toronto, Canada.

IPCC. 2001. *Climate Change 2001: The Scientific Basis*. (eds. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson). Cambridge University Press, Cambridge, U.K. and New York, U.S.A. 881pp.

Inoue, H. Y. and Matsueda, H. 2001. Measurements of atmospheric CO_2 from a meteorological tower in Tsukuba, Japan. *Tellus* **53B**, 205–219.

Keeling, C. D., Chin, J. F. S. and Whorf, T. P. 1996. Increased activity of northern vegetation inferred from atmospheric CO_2 measurements. *Nature* **382**, 146–149.

Kondo, H., Saigusa, N., Murayama, S., Yamamoto, S. and Kannari, A. 2001. A numerical simulation of the daily variation of CO_2 in the central part of Japan–summer case. *J. Meteorol. Soc. Jpn*. **79**, 11–21.

Lee, M., Nakane, K., Nakatsubo, T., Mo, W. and Koizumi, H. 2002. Effects of rainfall events on soil CO_2 flux in a cool-temperate deciduous broad-leaved forest. *Ecol. Res*. **17**, 401–410.

Levin, I., Graul, R. and Trivett, N. B. A. 1995. Long term observations of atmospheric CO_2 and carbon isotopes at continental sites in Germany. *Tellus* **47B**, 23–34.

Lloyd, J. and Taylor, J. A. 1994. On the temperature dependence of soil respiration. *Funct. Ecol*. **8**, 315–323.

Mariko, S., Nishimura, N., Mo, W., Matsui, Y., Kibe, T. and Koizumi, H. 2000. Winter CO_2 flux from soil and snow surfaces in a cool-temperate deciduous forest, Japan. *Ecol. Res*. **15**, 363–372.

Matsueda, H., Inoue, H. Y. and Ishii, M. 2002. Aircraft observation of carbon dioxide at 2–13 km altitude over the western Pacific from 1993 to 1999. *Tellus* **54B**, 1–21.

Morimoto, S., Nakazawa, T., Higuchi, K. and Aoki, S. 2000. Latitudinal distribution of atmospheric CO_2 sources and sinks inferred by δ^{13}C measurements from 1985 to 1991. *J. Geophys. Res*. **105**, 24 315–24 326.

Nakazawa, T., Ishizawa, M., Higuchi, K. and Trivett, N. B. A. 1997a. Two curve fitting method applied to CO_2 flask data. *EnvironMetrics* **8**, 889–906.

Nakazawa, T., Murayama, S., Toi, M., Ishizawa, M., Otonashi, K., Aoki, S. and Yamamoto, S. 1997b. Temporal variations of the CO_2 concentration and its carbon and oxygen isotopic ratios in a temperate forest in the central part of the main island of Japan. *Tellus* **49B**, 364–381.

Nakazawa, T., Sugawara, S., Inoue, G., Machida, T., Makshutov, S. and Mukai, H. 1997c. Aircraft measurements of the concentrations of CO_2, CH_4, N_2O and CO and the carbon and oxygen isotopic ratios of CO_2 in the troposphere over Russia. *J. Geophys. Res*. **102**, 3843–3859.

Raich, J. W. and Schlesinger, W. H. 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus* **44B**, 81–99.

Raich, J. W., Potter, C. S. and Bhagawati, D. 2002. Interannual variability in global soil respiration, 1980–1994. *Global Change Biol*. **8**, 800–812.

Rey, A., Pegoraro, E., Tedeschi, V., Parri, I. D., Jarvis, P. G. and Valentini, R. 2002. Annual variation in soil respiration and its components in a coppice oak forest in Central Italy. *Global Change Biol*. **8**, 851–866.

Saigusa, N., Yamamoto, S., Murayama, S., Gamo, M., Kondo, H., Fujinuma, Y. and Hirano, T. 2001. A long-term flux measurement over a cool-temperate deciduous forest by the eddy covariance method. In: *Proc. International Workshop for Advanced Flux Network and Flux Evaluation, CGER-Report M011*. 145–148.

Saigusa, N., Yamamoto, S., Murayama, S., Kondo, H. and Nishimura, N. 2002. Gross primary production and net ecosystem exchange of a cool-temperate deciduous forest estimated by the eddy covariance method. *Agric. For. Meteorol*. **112**, 203–215.

Tanaka, M., Nakazawa, T., Shiobara, M., Ohshima, H., Aoki, S., Fukabori, M., Kawaguchi, S., Yamanouchi, T., Makino, Y. and Murayama, H. 1987. Variations of atmospheric carbon dioxide concentration at Syowa station (69°00′S, 39°35′E), Antarctica. *Tellus* **39B**, 72–79.

Tans, P. P., Fung, I. Y. and Takahashi, T. 1990. Observational constraints on the global atmospheric CO_2 budget. *Science* **247**, 1431–1438.

Yamamoto, S., Murayama, S., Saigusa, N. and Kondo, H. 1999. Seasonal and inter-annual variation of CO_2 flux between a temperate forest and the atmosphere in Japan. *Tellus* **51B**, 402–413.