B-6.1.4 Research on the Modeling of Carbon Cycle in the Temperate Forest by CO_2 Flux and Isotopes Measurements

Contact person Susumu Yamamoto
National Institute for Resources and Environment, AIST, MITI
Onogawa 16-3, Tsukuba, Ibaraki 305-8569, Japan
Phone:+81-298-58-8360, Fax:+81-298-8358
E-mail: yamas@nire.go.jp

Total Budget for FY1996-FY1998 8,934,000Yen (FY1998; 2,978,000Yen)

Abstract The measurements of the atmospheric CO_2 concentration, flux, isotope and meteorological conditions using a tower in a temperate deciduous forest situated at the mountainous area of Japan (Takayama-city) were conducted from Oct.,1993 to Mar.,1999. Our objective of this research was to elucidate the carbon cycle in the temperate forest-ecosystem. Main results obtained in this research are as follows;

(1) The seasonal and inter-annual variations of CO_2 exchange between the atmosphere and a temperate deciduous forest and the relation of them to meteorological conditions and forest activity were investigated. Average net-uptake of CO_2 is 1.2 tC/ha /year, but it has notable variation due to the differences of insolation ,temperature and forest-activity in each year.

(2) Daily values of the net ecosystem production, NEP and the gross primary production, GPP of the forest were estimated from the CO_2 flux measurement, and they were parameterized as a function of the air temperature and the absorbed photosynthetic active radiation, APAR. The observed seasonal change in NEP was well simulated by this experimental equation.

(3) Diurnal variations of carbon and oxygen isotopic ratios in the warm season and seasonal variation of the carbon isotopic ratio were observed. From comparison with the CO_2 concentration variation, it was suggested that these variations reflect diurnal and seasonal variations of CO_2 exchange between the atmosphere and the biosphere.

(4) The emission inventory of CO_2 from anthropogenic origin and uptake-release rate of the ecosystem parameterized as a function of air temperature and the PAR were input to mesoscale chemical-transport model and analyzed the portion of CO_2 from anthropogenic origin and uptake-release of CO_2 by the biosphere.

Key Words Carbon Cycle, Temperate Forest, CO_2 Flux, Stable Isotopes, Transport Model

1. Introduction

Our knowledge of the sources and sinks of carbon on a global scale is not sufficient. Biosphere, in particular, forest ecosystems may be major sinks of carbon dioxide. However, recent estimation of carbon flux in the terrestrial biosphere has a high degree of uncertainty in the magnitude (for example Keeling et al. 1), Dixon et al. 2), IPCC3)).

CO_2 uptake was estimated by Wofsy et al.4) using continuous measurements of CO_2 flux longer than one year in a deciduous forest in central Massachusetts, USA. After this, the seasonal variations of flux and uptake of CO_2 in various forests at the different latitudes were investigated, for example, by Valentini et al.5), Black et al.6) and Malhi et al.7). According to their results, the forest ecosystems were sink of CO_2, but they had large variety. Therefore, we need more research on the role of the forest to the CO_2 budgets on a global scale. Baldocchi et al.[8) proposed the strategies for measuring and modeling of CO_2 and H_2O fluxes over forests and establishment of a network of the long-term measurements of fluxes using towers.

The objectives of this research are to elucidate the seasonal and inter-annual variations in CO_2 exchange between the atmosphere and a temperate forest, and to investigate the carbon cycle in the forest ecosystem, and also to estimate the portion of CO_2 from anthropogenic origin and uptake-release of CO_2 by the biosphere using mesoscale transport model.

2. Site of Measurement

The measurements of the atmospheric concentration of CO_2 and meteorological conditions using a tower (height=27m) in a temperate forest were started from October, 1993. The tower was set in the middle of Japan (36° 08' N, 137° 25' E) as shown in Fig.1. The tower was situated on one of the hills about 15 km east from Takayama City and the elevation of the site is about 1420m above sea level. The undulation of the surrounding area in radius of 500m is about 100 m. The inclinations of the slopes are about 1/10(6 degree) and 1/5 (12 degree) for the prevailing wind directions; SW and NE, respectively. The fetch length of this deciduous forest varies from 500 m to 1 km with wind direction. Annual mean temperature was about 7.3 ℃ and the monthly averaged temperature reached 20 ℃ in August and -4.8 ℃ in January.

The main species of trees in the site were deciduous broad-leaf trees such as birch (*Betula ermanii, Betula platyphylla*) and oak (*Quercus mongolica*), and average height of the trees (canopy height) was about 17 m. This is a protected forest, therefore human disturbances should be few during the recent 40 years. This site was covered by snow from December to April, and the beginning of June was the budding time and the beginning of October was the deciduous period of leaves.

3. Items of Measurement

(1) CO_2 concentration and flux, and meteorological conditions

The observational items of routine and long-team are listed in Table 1. Mean values of CO_2 concentration at 4 different heights of the tower were measured by NDIR gas analyzer. The CO_2 analyzer was calibrated by introducing four standard gases of 320 to 430 ppmv in dry air. The estimated precision of this system was better than 0.1 ppmv.

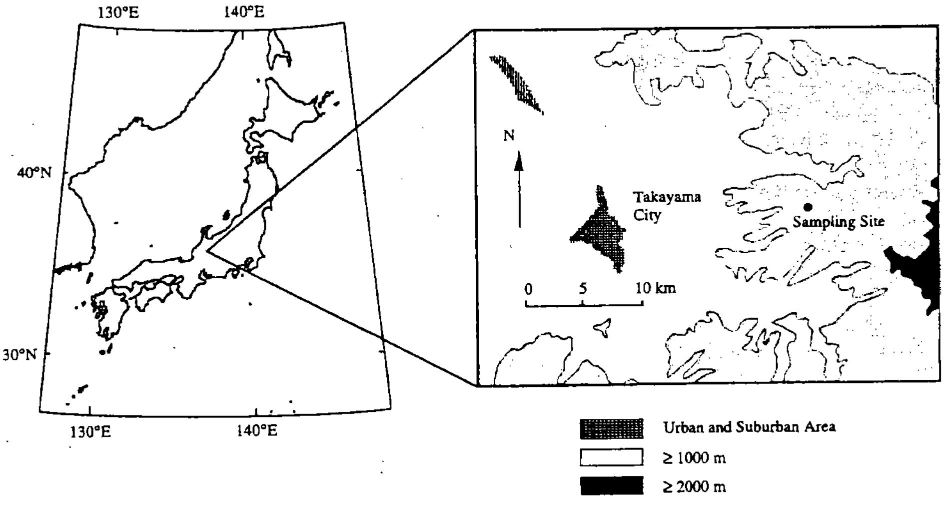

Fig.1 Map of the observation site.

Table 1 Observational items and heights in the atmospheric conditions.

Period	Observation Items	Observation Heights	Instruments
Routine Measurement (From October, 1993)	CO_2(mean value)	27, 18, 8.8, 5.8m	Non-dispersive infrared gas analyzer
	Insolation	25.5m	Pyranometer
	Wind speed and direction (mean)	26, 9.5m	Combined wind vane and fan anemometer
	Temperature and humidity (mean)	25.5, 9m	Platinum resistance thermometer and Humicap hygrometer
(From July,1998)	CO_2 and H_2O	24.5 m	Closed -path CO_2/H_2O analyzer
	Wind and temperature fluctuations	25 m	Ultrasonic anemometer and thermometer
Intensive Measurements	CO_2 and H_2O	24.5, 11m	Open-path CO_2/H_2O analyzer
	Wind and temperature fluctuations	25 , 10m	Ultrasonic anemometer and thermometer

In addition, after July 25, 1998, the fluxes of sensible heat, water vapor, and CO_2 were measured by the eddy covariance method. Fluctuations of CO_2 and water vapor concentrations were measured by a closed-path type infrared gas analyzer (model LI-6262, LI-COR). The air inlet was fixed at 25.0 m in height, and the air was drawn down through a Teflon tube with 35 m long and 3.0 mm inner diameter, then it was pumped into sample cell at 4.0 L min-1. The gain of CO_2 of the analyzer was checked once a day by flowing two CO_2 standard gases of 320 and 420 ppmv. And also, the photosynthetic active radiation PAR was measured by quantum sensors at 19.5 m (above the canopy), and 2.0 m (below the canopy).

(2) Stable isotope measurement of CO_2

Air samples were taken over a few days in every month, and their sampling interval was set to about 2 hours to detect the diurnal variations of the CO_2 concentration and its carbon and oxygen isotopic ratios (d13C and d18O) (refer Nakazawa et al.,[9] in details). Each air sample at 18 m height was collected into a glass flask using a diaphragm pump. After a NDIR analysis for the CO_2 concentration, pure CO_2 was extracted cryogenically from the remaining air in the flask and d13C and d18O of the CO_2 samples were measured by a mass spectrometer.

(3) CO_2 flux measurement at the ground surface

The measurement of the CO_2 flux at the ground surface was carried out once per month using a closed chamber method. Air samples in the chamber were taken into evacuated glass flasks every 10 min for 45-50 min after closing the chamber. The pressure of the air sample and temperatures in the chamber and the soil near the surface were measured. To measure the concentration, pure CO_2 was extracted cryogenically from the air in the flask, and the amount of CO_2 was determined manometrically in a calibrated volume using a precise pressure sensor.

4. Analytical Method for CO_2 Flux

The flux of CO_2 was calculated by the aerodynamic method (refer Yamamoto et al.[10]) and the eddy covariance method. In the aerodynamic method, CO_2 flux was determined based on the vertical gradient of the CO_2 concentration and diffusion coefficient estimated from the mixing length theory. In present study, the flux of CO_2 throughout the whole year was calculated using the aerodynamic method. In eddy covariance method,CO_2 and H_2O flux were computed directly using data of CO_2 , H_2O fluctuations and turbulence of vertical wind. The sampling duration and frequency for the calculation of CO_2 flux were taken 30 minutes and 5

Hz, respectively. CO_2 flux obtained with the eddy covariance was applied to the density fluctuation correction by Webb et al.[11)]. A coordinate rotation for the vertical wind velocity, the time shifting for the lag required to draw air, and the removal of the linear trends have been made. The flux loss in the high frequency for the closed-path system was not larger than about 5 % of total flux in the most case, and it was neglected in this study.

5. Analysis of CO_2 transportation using mesoscale- numerical model

(1) Estimation of CO_2 emission inventory

Total amount of anthropogenic emission of CO_2 in each category is summarized in Table 2. This amount is 6% less than the second report of Japan under the FCCC.

Table 2 Emission of CO_2.

Emission categories	amount(1000tC/y)	Emission categories	amount(1000tC/y)
large plant facilities	157,931	automobile	61,431
small plant facilities	59,152	ship	1,827
offices	8,622	airplane	758
domestic	18,852		

(2) Parameterization of uptake and release rate from forest ecosystem

The uptake rate of CO_2 from forest ecosystem (A) was parameterized as follows.

$$A = \frac{bI}{1+aI} - R,\ R = R_{25}Q^{\frac{T-25}{10}}$$

Here, R is CO_2 release of respiration, R_{25} is the value of R at 25°C. R_{25} and Q are assumed to $0.078 mgCO_2m^2s^{-1}$ and 2 in the present work independent of plant species. The values of a and b are given by Schulze et al.[12)] in Table 3.

Table 3 a, b and G_S of various plant species.

No.	Land use	G s mms^{-1}	a $J^{-1}\ sm^2 \times 10^{-5}$	b $mgCO_2\ J^{-1} \times 10^{-3}$
1	ever green broad leaf shrub	9.4	6.80	0.79
2	ever green conifers	20.6	6.80	1.71
3	decidous conifers	11.4	6.80	0.95
4	decidous broad leaf tree	20.7	6.80	1.72
5	ever green broad leaf tree	12.1	6.80	1.01
6	mixed forest	13.8	6.80	1.15
7	temperate grass land	23.0	6.80	1.92
8	bog	5.0	6.80	0.42
9	arable cropland	32.5	6.80	2.70
10	rice	25.1	6.80	2.08
11	urban	--	--	--
12	water	∞	--	--

(3) Transportation model

The model used for the calculation of CO_2 transportation is NIRE-MM (Kondo [13)]). The model is hydrostatic, Boussinesq approximated model and the calculation was executed over central Japan. The transportation of CO_2 is calculated with NIRE-MM in terrain-following coordinate system and CO_2 emission and uptake inventory.

6. Results and Discussions

6.1 Seasonal and inter-annual variation of the CO_2 uptake rates

The seasonal variation of CO_2 flux, snow condition and leaf- stem area index (LAI) in 1997 is shown in Fig. 2. There is snow accumulation from December to April in this site. LAI of this forest was about 3.5 from June to September. The extension time of leaves is the end of May and deciduous period of leaves is the beginning of October. The ground surface was covered by bamboo. Net of uptake of CO_2 is positive (uptake by the forest ecosystem) from May to October and negative (outgoing to the atmosphere) from November to April. After the period of snow-melting, CO_2 flux in night-time become negative and the release rate of CO_2 from soil in summer and autumn is larger than the other seasons due to high temperature.

Fig. 3 shows the inter-annual variations of integrated uptake rate of CO_2 for daytime, night and whole day for each month from October,1993 to December,1998. The integrated uptake amounts of CO_2 for daytime, night and whole day in each year from 1994 to 1998 are listed in Table 4. In the calculation of CO_2 flux, the flatness and homogeneity of the site are assumed, but the topographical conditions of this site are not so ideal. In this study, the errors of CO_2 flux due to topographical conditions were investigated through comparison with heat budgets under hypothesis of the similarity between heat and CO_2 fluxes. Then, CO_2 uptake rate estimated by tower measurement might be underestimation of 40%, therefore, the result in Table 4 should be multiplied by 1.7.

We can consider following three factors for the causes of above difference in the CO_2 uptake in these years.

(1) Activity of rainy season in June and July

There is rainy season during June and July in Japan, but it has big difference of activity of rainy season, that is, wet type as 1995, 1997 and dry type as the other years. For example, the uptake rate of CO_2 in June-July,1995 was 63% of the value in June-July, 1994. The insolation in June and July, 1995 was less than the other years and the temperature in June,1995 was lower than 1994 by 2.5 ℃. Fig.4 shows the relations of temperature and insolation with integrated-uptake of CO_2 in June, July, August and September during 1994 to 1997.

(2) Yearly variation of snow condition and temperature in spring

The melting time of snow was at the end of April in 1996 and at the beginning of April in 1997 and 1998. The differences of snow condition and temperature in spring can be affected in the activity of soil respiration and photosynthesis of bamboo(floor plant). After snow-melting, temperature of the ground-surface can become high and insolation can be reached directly to the leaves of bamboo under the condition without tree-leaves.

(3) Variation of active period of the forest estimated from LAI

According to the analysis of LAI, extension time of tree leaves in 1998 is two weeks earlier than that in 1997 and three weeks earlier than that in 1996. Considering the shortness of active season of the trees in this site (4 months), the difference, 20 days of extension time of leaves has a potential of 17 % (=20 days/120days) difference in CO_2 uptake by trees.

6.2 Estimation of GPP and NEP using flux and respiration data and their modeling

The eddy covariance measurement has started on 25 July 1998, and the data set from 25 July to 28 October was used. The ecosystem respiration, Rec were estimated from flux

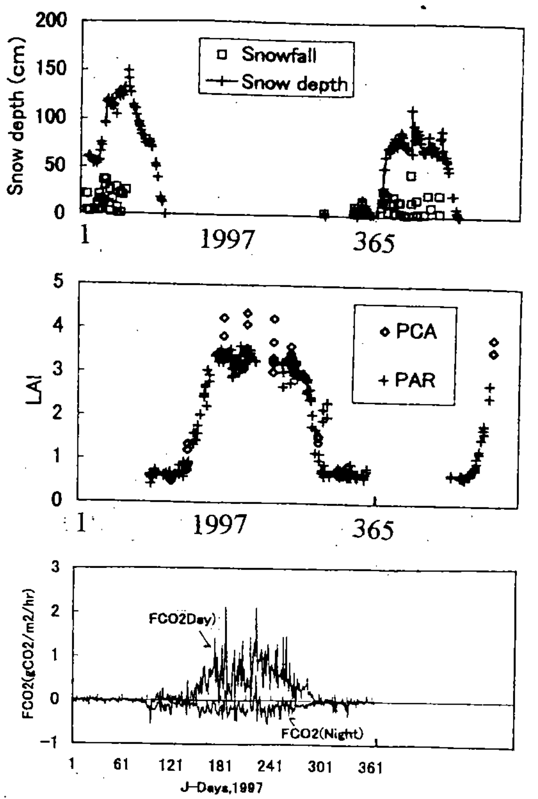

Fig. 2 Seasonal variation of snow-depth, leaf and stem area index (LAI) and FCO2 in 1997.

Table 4. Integrated uptake rate of CO_2 (gC/m^2 /year) for daytime, night and whole days in 1994 to 1998.

Year	Q(Whole)	Q(Day)	Q(Night)
1994	112	256	-144
1995	67	189	-122
1996	136	239	-103
1997	149	263	-114
1998	138	261	-123
Mean	120	241	-121

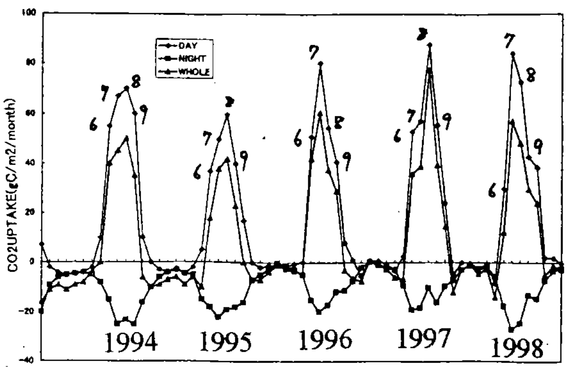

Fig 3 Seasonal and inter-annual variation of integrated uptake rate of CO_2 for daytime, night and whole day, in each month from Oct.1993 to Dec.1998.

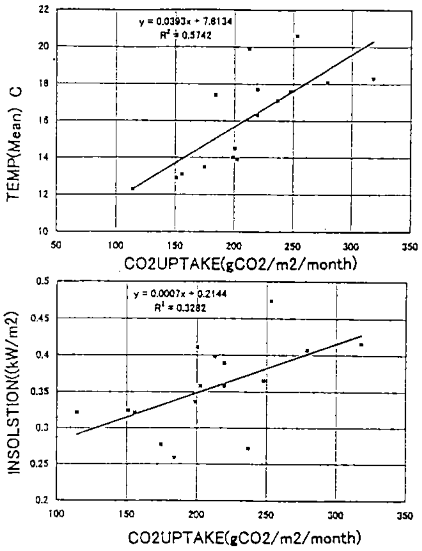

Fig.4 Integrated uptake rate of CO_2 and monthly mean temperature and insolation for daytime in each month from June to September during 1994 to 1997.

measurement in the nighttime. However, Rec in the stable atmospheric condition were often less than Rsoil measured by the Institute for Basin Ecosystem Studies, Gifu University (Nishimura[14)]) and our group. In this study, the relation between Rec and the nighttime air temperature T was expressed as follows for the nearly neutral condition.

$$\mathrm{Rec} = A\,Q^{(T-10)/10} \qquad (1)$$

Here, Q and A are the constants listed in Table 5. In the following analysis, Q = 2.5, A= 0.20 μmolCO$_2$ m-2 s-1 were used. The daily values of NEP were calculated by integrating the CO_2 flux over the canopy. The daily values of GPP were estimated by daily NEP and Rec calculated by Eq.(1) using the daily mean of air temperature. Regarding to a seasonal change in LAI from July to October, the GPP was parameterized by the daily absorbed photosynthetic active radiation, APAR. Fig. 5 shows the relation between GPP and APAR. Symbols show the daily GPP from 25 July to 28 October, and lines show the experimental equation between

GPP and APAR as follows.

$$GPP = a\ APAR / (1 + b\ APAR) \qquad (2)$$

Here, a and b are the constants, and Table 6 shows the monthly values of b and b/a as a result of the regression of the GPP to Eq.(2).

On the analogy of the light-photosynthesis relationship of individual leaf, the meaning of the constant b is the light use efficiency of the canopy, and the constant b/a is the maximum rate of CO_2 fixation of the canopy. From July to October, the constant b had decreased about 20 % (from 0.071 to 0.057), and b/a about 70 % (from 1.53 to 0.47). It was speculated that there was a remarkable decrease in the maximum rate of CO_2 fixation in the individual leaves.

Using Eqs. (1) and (2), the daily NEP is summarized as the following equation.

$$NEP = a\ APAR / (1 + b\ APAR) - A\ Q^{(T-10)/10} \qquad (3)$$

Fig. 6 shows a seasonal change in the observed NEP and the calculated NEP. Observed NEP was the daily sum of the CO_2 flux, and the calculated NEP was estimated by Eq.(3) using the daily APAR and the daily mean air temperature, with parameters listed in Tables 5 and 6. The observed and calculated NEP reached up to 0.6 mol m-2 day-1 during July and August (DOY 206-243), and it gradually decreased in September (DOY244-273) with the decrease in LAI. The seasonal change in the observed NEP was well simulated by a simple experimental equation (Eq. 3) during the observational period.

6.3 Temporal variation of the concentration and Stable isotopic ratios of CO_2

Fig. 7 shows the monthly mean CO_2 concentrations at the 27 m height calculated from the daily mean values and the standard deviations from the monthly mean values. The CO_2

Table 5 Parameters expressing the relation between the Rec and nighttime air temperature.

Q	2	2.5	3
A (molCO2 m-2 day-1)	0.22	0.20	0.18
r2	0.36	0.38	0.37

Table 6 Parameters expressing the relation between the GPP and APAR.

	b	b/a	r^2
	(molCO$_2$ / mol photon)	(molCO$_2$ m-2 day-1)	
Jul.	0.071	1.53	0.84
Aug.	0.089	1.35	0.55
Sep.	0.064	1.19	0.55
Oct.	0.057	0.47	0.60

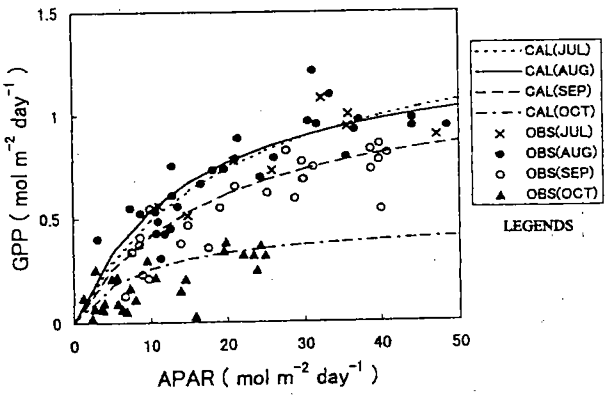

Fig. 5 The relation between the GPP and the APAR. Symbols show the daily GPP from 25 July to 28 October. Lines represent the experimental equation (Eq. 2) with monthly parameters listed in Table 6.

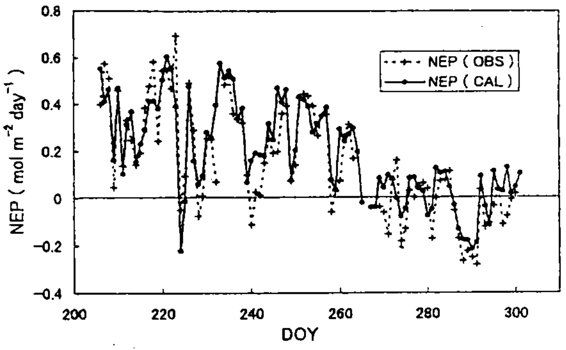

Fig. 6 Seasonal changes in the daily NEP from 25 July to 28 October. Dashed line with pulses is the observed NEP, and solid line with closed circles is the calculated NEP by Eq. (3).

concentration shows a prominent seasonal variation with the maximum in late April, the minimum in mid-September and 11ppmv of the peak-to-peak amplitude on average, reflecting the seasonal variation of the biological activities near the site. The secular increase of 1.9 ppmv/year is also seen. Fig.8 shows seasonal variations of the monthly mean of diurnal amplitude of the CO_2 concentration over the forest (27 m) in 1996-1998. It is found from this figure that the diurnal amplitude is large in the biologically active season from May to October.

Fig. 9 shows the typical diurnal variations of the atmospheric CO_2 concentration, its carbon isotopic ratio (d13C) and oxygen isotopic ratio (d18O) over the forest in warm and cold seasons. d13C shows a prominent diurnal variation with high values in the daytime and low values in the nighttime, especially during the warm season. d13C also varies seasonally, showing a maximum in summer and a minimum in spring.The diurnal and seasonal variations of d13C were opposite in phase with those of the CO_2 concentration. The rate of change in d13C with respect to the CO_2 concentration was found to be approximately -0.05 ‰ ppmv. This suggests that the diurnal and seasonal variations of the CO_2 concentration are produced primarily by diurnally- and seasonally-dependent photosynthetic-respiratory processes of the biosphere near the site, respectively. As seen in Fig. 9, d18O also increases in the daytime and decreased in the nighttime in the warm season, which is similar to the diurnal variation of d13C.

6.4 Estimation of the contamination of CO_2 from anthoropogenic sources

Calculation is executed for the period from 20 to 23 July, 1997. The meteorological data from the RSM of JMA (about 40km by 40km resolution) are used to introduce the large scale

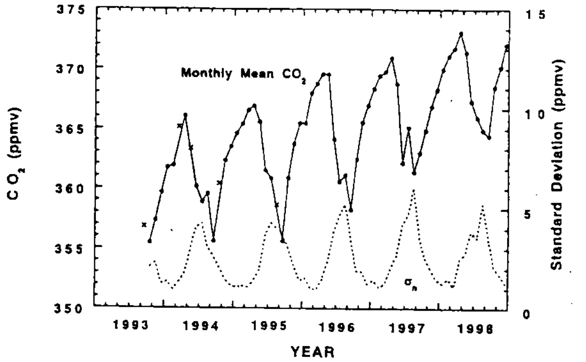

Fig. 7 Monthly mean CO_2 concentrations at the 27 m height calculated from the daily mean values and the standard deviations from the monthly mean values.

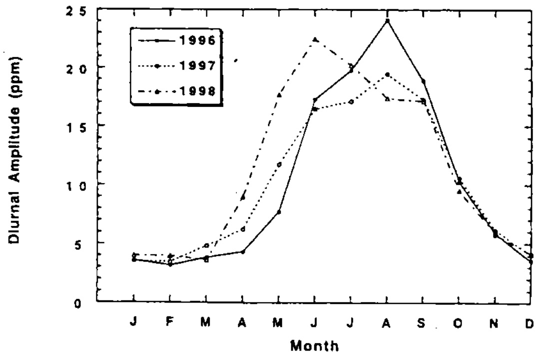

Fig. 8 Seasonal variations of the monthly mean of diurnal amplitude of the CO_2 concentration at the 27 m height in 1996-1998.

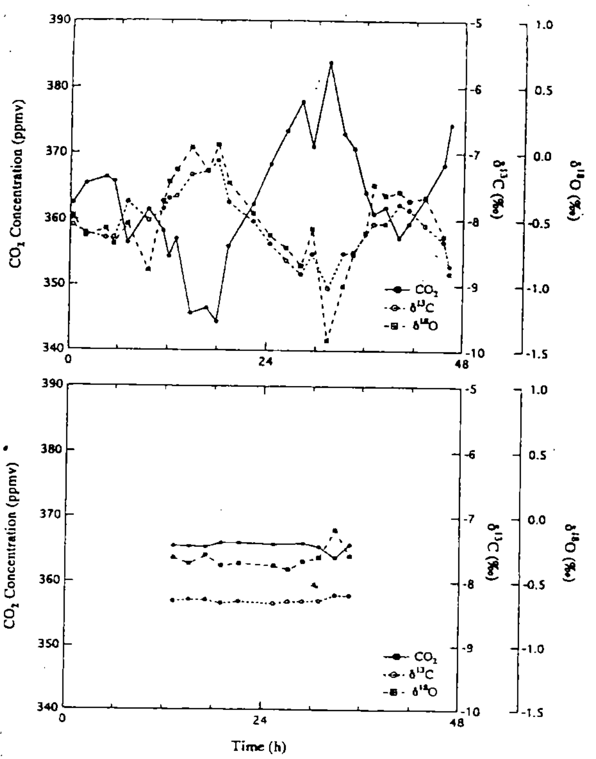

Fig.9 Typical diurnal variations of the CO_2 concentration and its d13C and d18O observed at the 18 m height for summer (upper panel) and winter (lower panel).

effect every three hours. The vertical profiles of CO_2 at Takayama and offshore of Omaesaki are shown in Fig.10. The data obtained by airplane are also shown in Fig.11. The profile is quite similar between the observation and calculated results in Takayama, but not so much for Omaesaki. The background level is a little high at Omaesaki in the observation. Fig. 12 shows daily variation of CO_2 at 27m tower in Takayama. The contamination from Tokyo, Nagoya and Takayama area are also shown in Fig.13. The contamination from Nagoya is as much as 3ppm in the morning on July 23.

7. Conclusions

Seasonal and inter-annual variations of CO_2 exchanges between the atmosphere and a temperate forest in Japan were investigated through tower measurements from October,1993 to December, 1998. And the portion of CO_2 concentration from anthropogenic origin and uptake-release of CO_2 by the biosphere were analyzed using mesoscal-transport numerical model. Main results in this study as follows;

(1) The net of uptake rate of CO_2 was positive (uptake by forest) from May to September and negative (release to the air) from October to April. Averaged uptake amount of CO_2 in a year

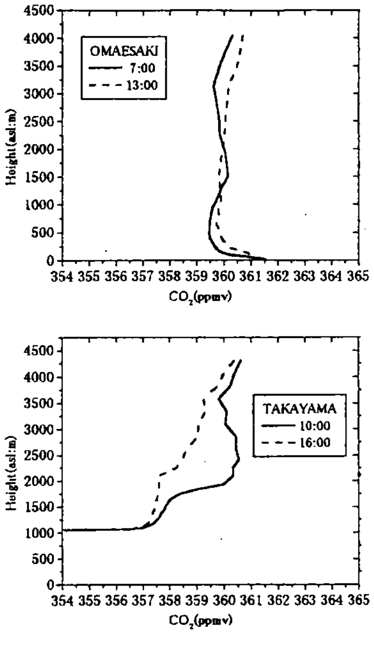

Fig.10 CO_2 profiles obtained from the calculation.

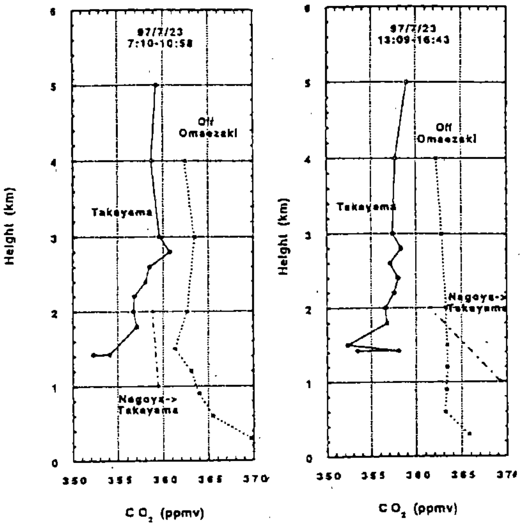

Fig.11 Profile of CO_2 at Takayama and Omaesaki.

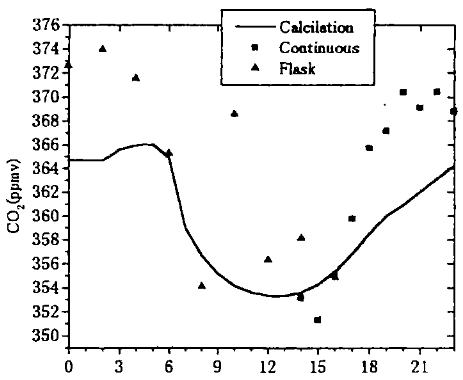

Fig.12 Comparison of concentration of CO_2 between the model and observation on July 23 at Takayama.

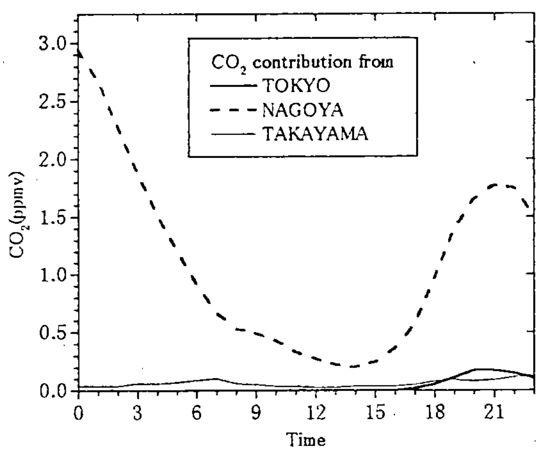

Fig.13 Estimated anthropogenic CO_2 which contaminated Takayama site from Tokyo, Nagoya Takayama city areas on July 23, 1997.

was 1.2 tC/ha/year, but it had notable inter-annual variation due to the differences of insolation, temperature, snow conditions and extension time of tree leaves. This result indicates the possibility of change of uptake of CO_2 by forest ecosystems induced by the climate change in regional/global scale.The errors of CO_2 flux due to topographical conditions were investigated through comparison with heat budgets. CO_2 uptake estimated by tower measurement might be underestimation of 40%, therefore, above value, 1.2 become 2 tC/ha/year.

(2) Daily values of the net ecosystem production NEP and the gross primary production GPP of the forest were estimated by the CO_2 flux measurement, and they were parameterized as a function of the air temperature and APAR. The result showed that the observed seasonal change in NEP was well simulated by the simple experimental equation.

(3) Diurnal variations of carbon and oxygen isotopic ratios in the warm season and seasonal variation of the carbon isotopic ratio were observed. From comparison with the CO_2 concentration variation, it was suggested that these variations reflect diurnal and seasonal variations of CO_2 exchange between the atmosphere and the biosphere.

(4) The emission inventory of CO_2 from anthropogenic origin was summarized. And uptake and release rate of the ecosystem was simply parameterized as a function of air temperature and APAR. Both data were input to mesoscale transport model and the anthropogenic contamination from Tokyo, Nagoya and Takayama areas were analyzed.

According to present study, the forest ecosystems can be a large sink of CO_2, but it needs more data of CO_2 flux in the forests of various types and latitudes to reduce the uncertainty of estimation of CO_2 uptake on the global scale and more quantitative study about the errors of the tower measurement. Moreover, the present results should be compared with the ecological direct-survey of photosynthesis, respiration, growing rate and litter fall of the forest ecosystem.

Acknowledgments

The authors would like to express their appreciation to all the members of Institute for Basin Ecosystem Studies, Gifu University for their cooperation and useful comments. This study was supported by the global environment research program of the Environment Agency of Japan.

References

1) Keeling,R.F. and Shertz,S.R. (1992) Nature 358,723-727.
2) Dixon,R.K.,Brown,S.,Houghton,R.A. and et al.(1994) Science 263,185-190.
3) IPCC (1995) Climate change 1995 - The Science of climate change.
4) Wofsy, S.C.,Goulden, B.C. and et al. (1993) Science 260,1314-1317.
5) Valentini, R., De Angelis, P. and et al.(1996) Global Change Biology 2,199-207.
6) Black ,T.A., Hartog, G.D. and et al. (1996) Global Change Biology 2,219-229.
7) Malhi ,Y., Nobre, A.D., and et al. (1998) Geophysical Research in press.
8) Baldocchi, D.,Valentini, R. and et al. (1996) Global Change Biology 2,159-168.
9) Nakazawa, T., Murayama, S. and et al. (1997) Tellus, 49B, 364-381.
10) Yamamoto,S., Murayama, S., Saigusa, N. and Kondo,H. (1999) Tellus, 50B, to appear.
11) Webbs, E.K, Pearman, G.J. and Leuning, R. (1980) Quart. J. R. Met. Soc.106, 85-100.
12) Schulze, et al.(1994) Ann. Rev. Ecol.Syst., 25:629-660.
13) Kondo,H. (1995) J. Appl. Met., 34, 1439-1448.
14) Nishimura,N. (1997) Annual report of the Global Research Fund of the Japan Environment Agency.