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A FEATURE OF CARBON DIOXIDE VARIATION IN A DECIDUOUS FOREST : AN EXAMPLE AT KAWATABI

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Abstract

A series of measurements of carbon dioxide were carried out in a deciduous forest to understand a role of vegetation on carbon cycle. The seasonal variations of photosynthesis and soil respiration in a forest were confirmed. A model on variation of carbon dioxide is proposed based on the satellite observation of vegetation. Physical parameters are determined through published data and the relationship between NPP and LAI. Although the model does not take the effect of diffusion into consideration, the results make possible to discuss the feature of carbon dioxide in the forest.

KEYWORDS: *carbon dioxide cycle, photosynthesis, deciduous forest, NDVI*

1. Introduction

The importance of vegetation on carbon cycle has been widely recognized. Cycle of carbon in forests is shown in **Fig. 1** schematically(Oikawa,1987). CO_2 in the atmoshpere is fixed through photosynthesis on leaves as gross primary product(GPP) P_g and stored in form of hydrocarbon onto leaves, branches and trunks $P_g(C)$, and roots $P_g(U)$. A part of them is transfered to soils as litter fall(L_F, L_C and L_U). On the other hand, CO_2 is supplied from forests to atmoshphere through respiraton of trees(R_F, R_C and R_U) and decomposition or respiration of organic matter in soil R_M. In this cycle, the difference of P_g and total respiraton of vegetaton is defined as net primary product(NPP) P_n as $P_n = P_g - (R_F + R_C + R_U)$.

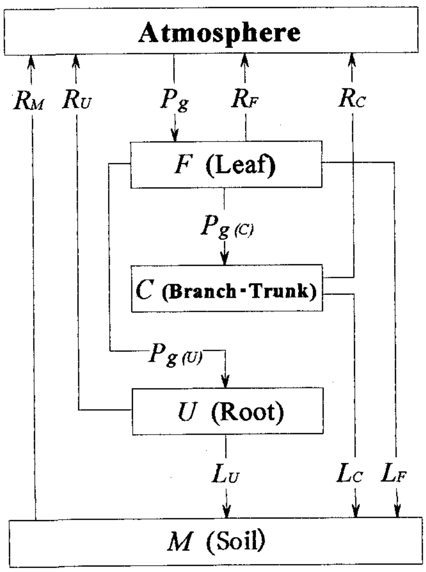

Figure 1. Cycle of carbon in forests(Oikawa:1987)

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Although the elementary processes have been studied in detail, it is still not so easy to evaluate this cycle quantitatively in forests with wide area. The first difficulty is that only few terms are measurable directly in this system. Leaf Area Index(LAI) is one of measurable quantities. It have been confirmed that Normalized Difference Vegetation Index(NDVI) observed by satellites has a good correlation with LAI. It is also known that NDVI correlates with the photosynthesis (Field et al.1995, Seller et al.1994 and Tucker et al.1986).

CO_2 concentration and CO_2 upward flux $R_F + R_C + R_U + R_M$ are also measurable on the ground. For example, Yasuda et al.(1998) measured CO_2 flux over a deciduous forest. However, those are variate widely both in space and time because of turbulent diffusion and convection in open system of atmosphere. This is the second difficulty.

The purpose of this study is to understand a basic feature of CO_2 in forests and to connect it to the vegetation activity observed by NOAA satellite. For this purpose, firstly, some series of measurements of CO_2 in a deciduous forest at Kawatabi, Miyagi Prefecture, Japan were carried out. Secondly a model is proposed to describe the observed results. In the model, some coefficients were evaluated so that the model is consistent with the satellite observed vegetation activity and NPP evaluated on the ground.

2. Measurements of CO_2 variation at Kawatabi

2.1 Setup of measurements

Measurements were carried out in Kawatabi Farm of Tohoku Universtity. It is located at 38°45′N and 140°46′E in Tohoku district, Japan. The farm consists of rice paddy and vegetable farm and is surrounded by dense forest with about 10m height as shown in **Fig. 2**. Although some cedars(*Cryptomeria japonica*) are planted artificially in part, almost all trees are deciduous one like beeches (*Fagus crenata*), oaks(*Quercus crispula, Quercus acutissima*) and so on, those of which are commonly observed in this district.

Two kinds of measurements were done in 1996 and 1997.

One is six series of intensive measurements(11-12 Sep. 1996; 14-18 May 1997; 4-6 Jul. 1997; 4-11 Sep. 1997; 23-29 Oct. 1997; 16-20 Dec. 1997). Beside the data in the forest mentioned below, CO_2 concentration and various meteorological data were obtained at three points; top(at 15m height:a few meter higher than canopy) and base(1m height) of the tower and rice paddy(1m height), indicated in **Fig. 2**.

The other is a continuous measurement at the point indicated "forest" in **Fig. 2** from August, 1996 to December,1997. A CO_2 meter and a temperature senser were set in a screen and CO_2 concentration and temperature variation in the forest at about 1 m height were measured in every hour for about sixteen months. Related meteorological data at AMeDAS(Automated Meteorological Data Aquisition System; Japan Meteorological Agency) station of Kawatabi and others were also collected and utilized in analysis. All of them are summerized in **Table 1**.

For continuous measurement of CO_2 concentration, portable environmental CO_2 meters, ZFP5(Fuji Electric Instrumemts Co.), were utilized. It was confirmed that this instrument is sensible of not only CO_2 concentration but also temperature variation because of Non-Dispersive Infra-Red Gas Analyzer system(NDIR). Therefore, the detail calibration of dependence on temperature was done at first and the output signal of the meter was converted to the CO_2 concentration by considering temperature measured simultaneously. In case of intensive measurements, atmosphere was sampled into flasks and analyzed by a gas chromatography

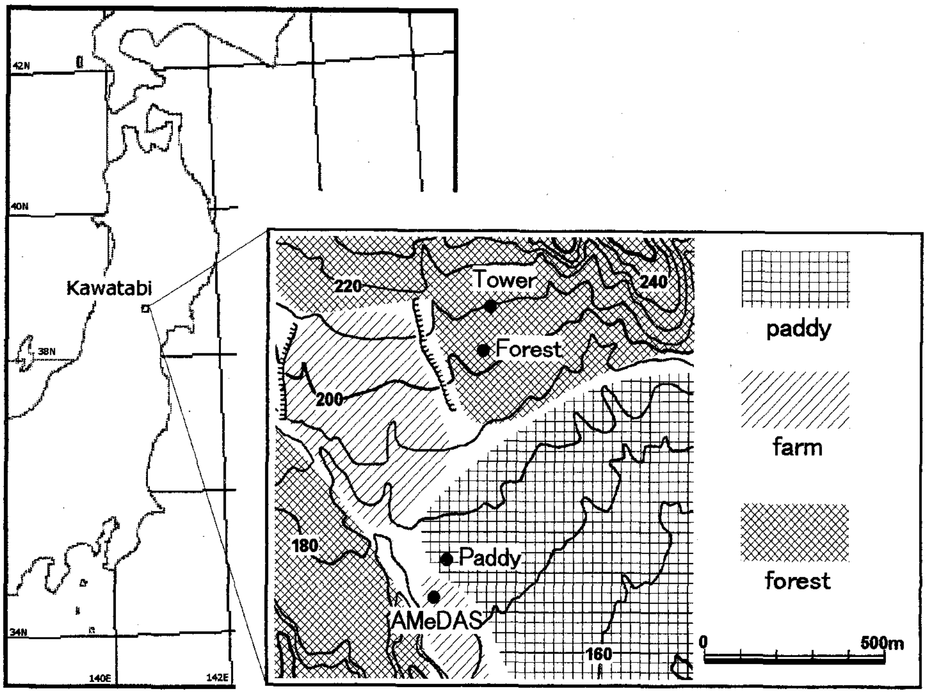

Figure 2. Map of Kawatabi

Table 1. Items and Instruments for measurement

Item	Instrument / Organizaton	Intensive	Continuous
CO_2 concentration	Environmental CO_2meter	○	○
CO_2 concentration	Gas Chromatography	○	–
Temperature	Thermister senser	○	○
Solar radiation	Solar Radiation Meter	○	–
Wind speed	Anemometer	○	–
Temperature	AMeDAS	○	○
Duration of sunshine	AMeDAS	○	○
Precipitation	AMeDAS	○	○
Wind direction・speed	AMeDAS	○	○
Solar radiation	Miyagi Pref. Agr. Center	○	○
NOAA/AVHRR for NDVI	Tohoku Univ., Comp. Center	○	○

with accuracy of 0.1ppmv simultaneously and the calibration of CO_2 meter was confirmed to have enough accuracy.

2.2 Results of measuremnents

Four examples of intensive measurements in 1997 are shown in **Figs.3**, **4**, **5** and **6**.

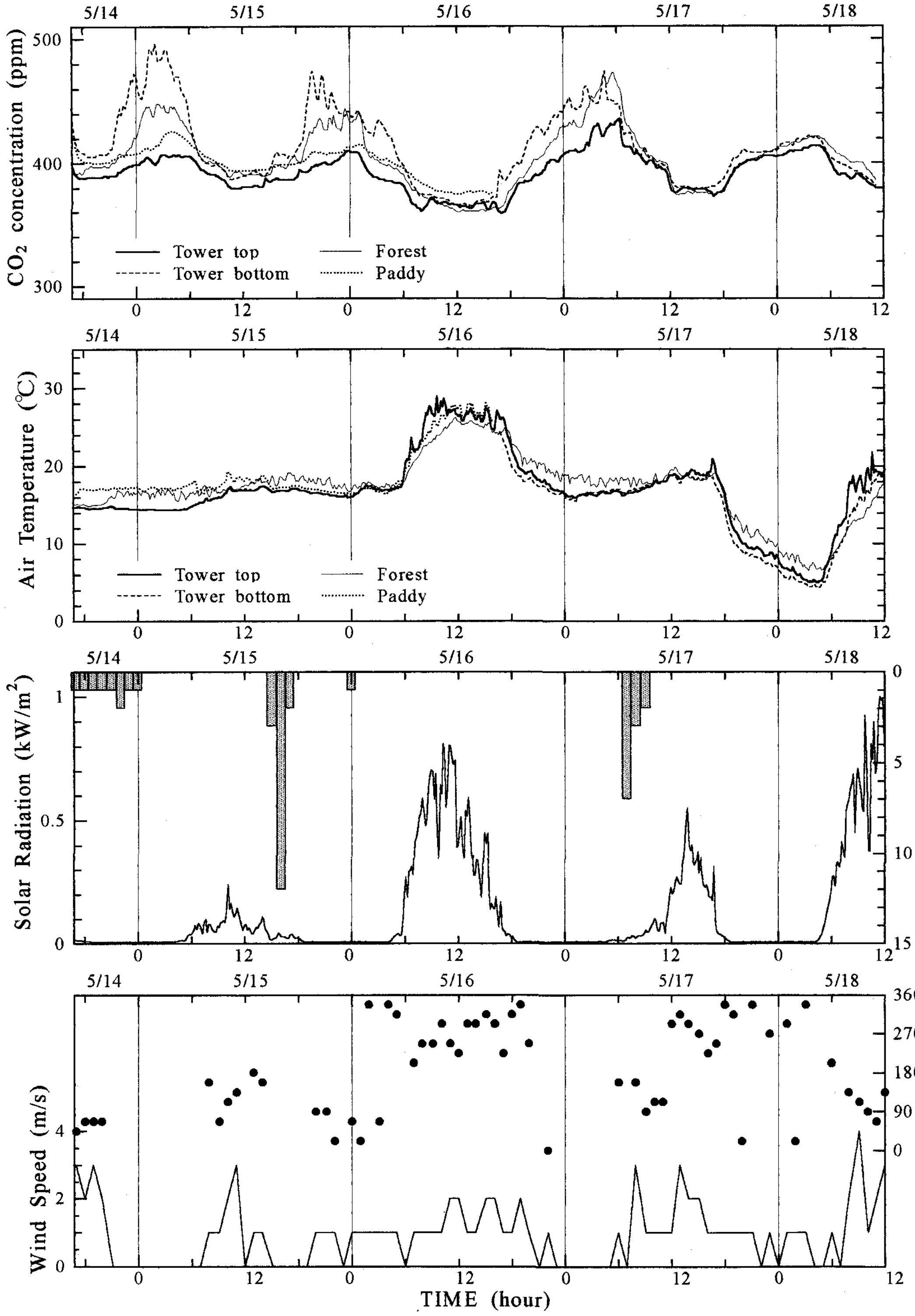

Figure 3. Results: May, 1997

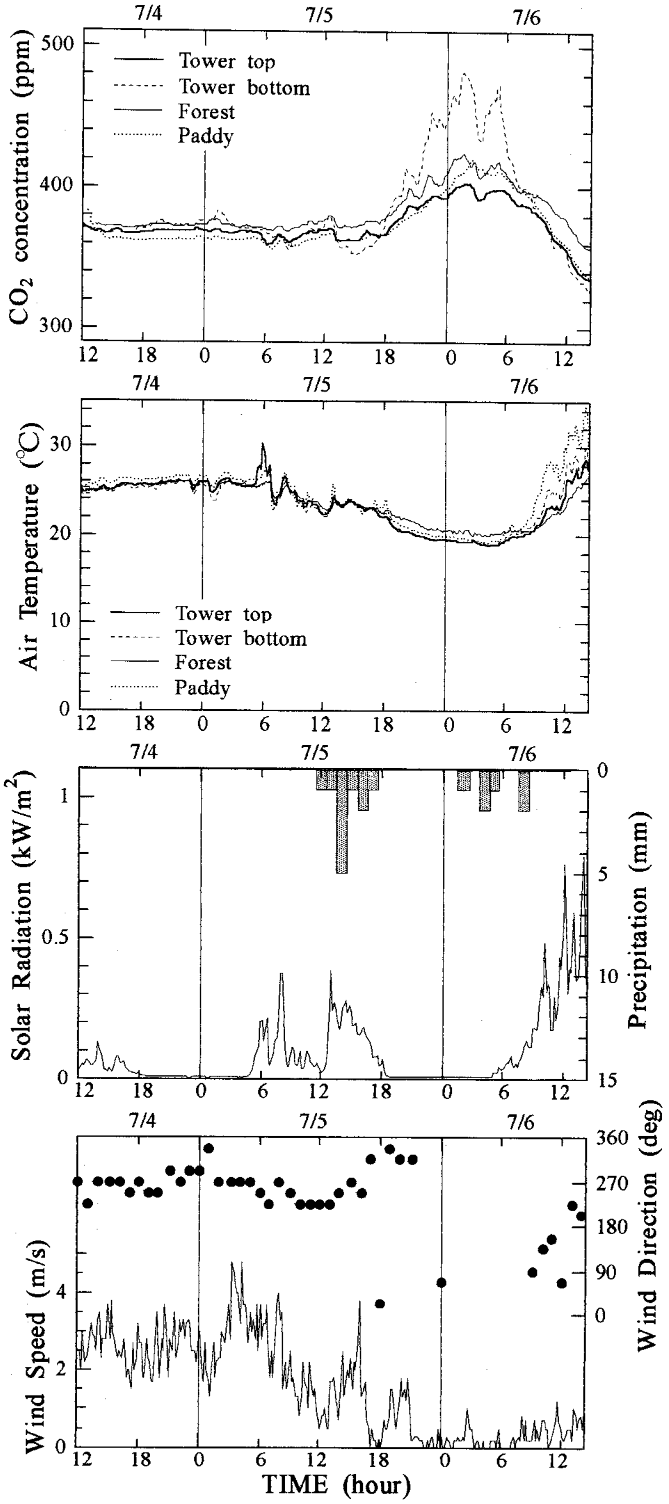

Figure 4. Results: July, 1997

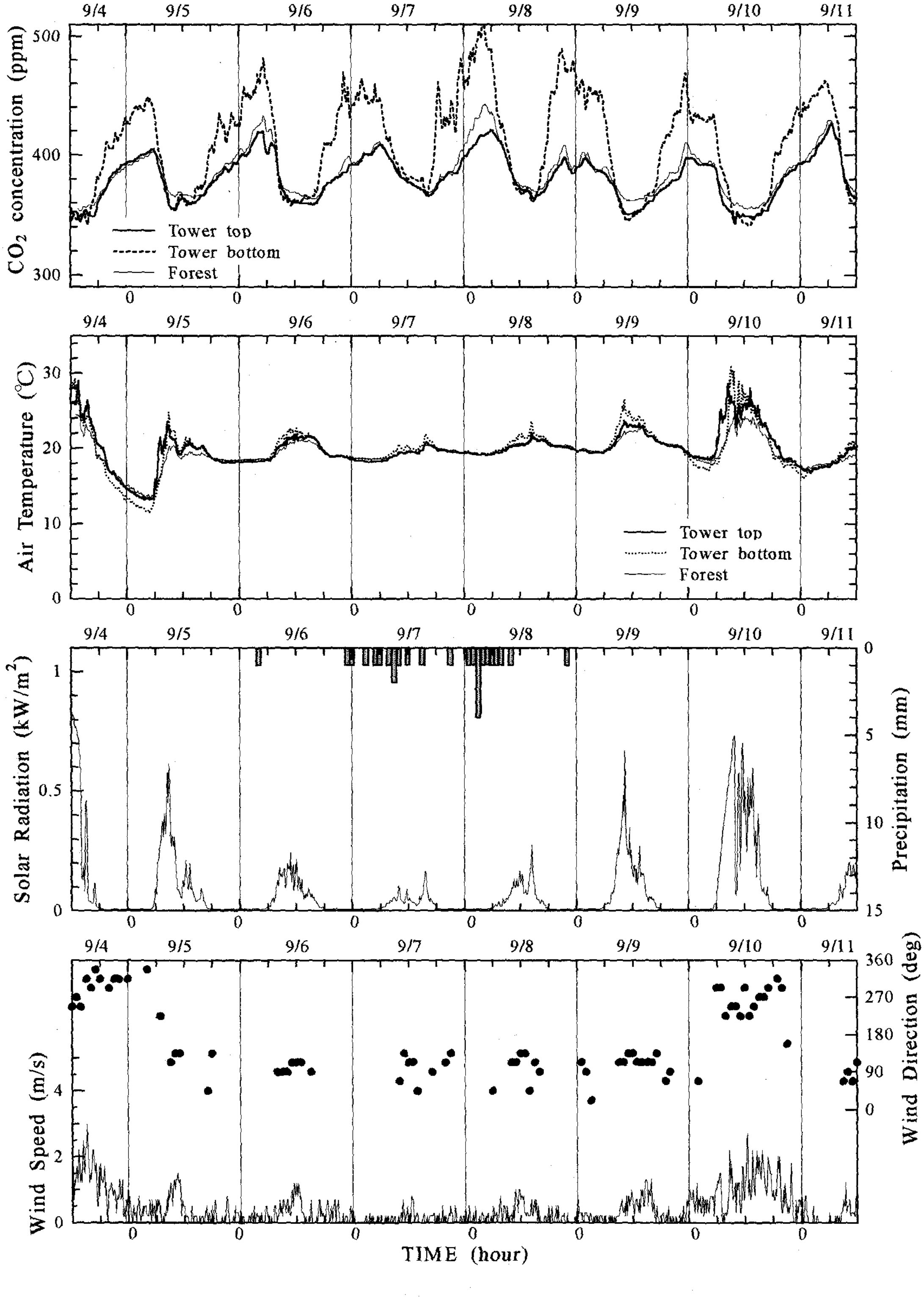

Figure 5. Results: September, 1997

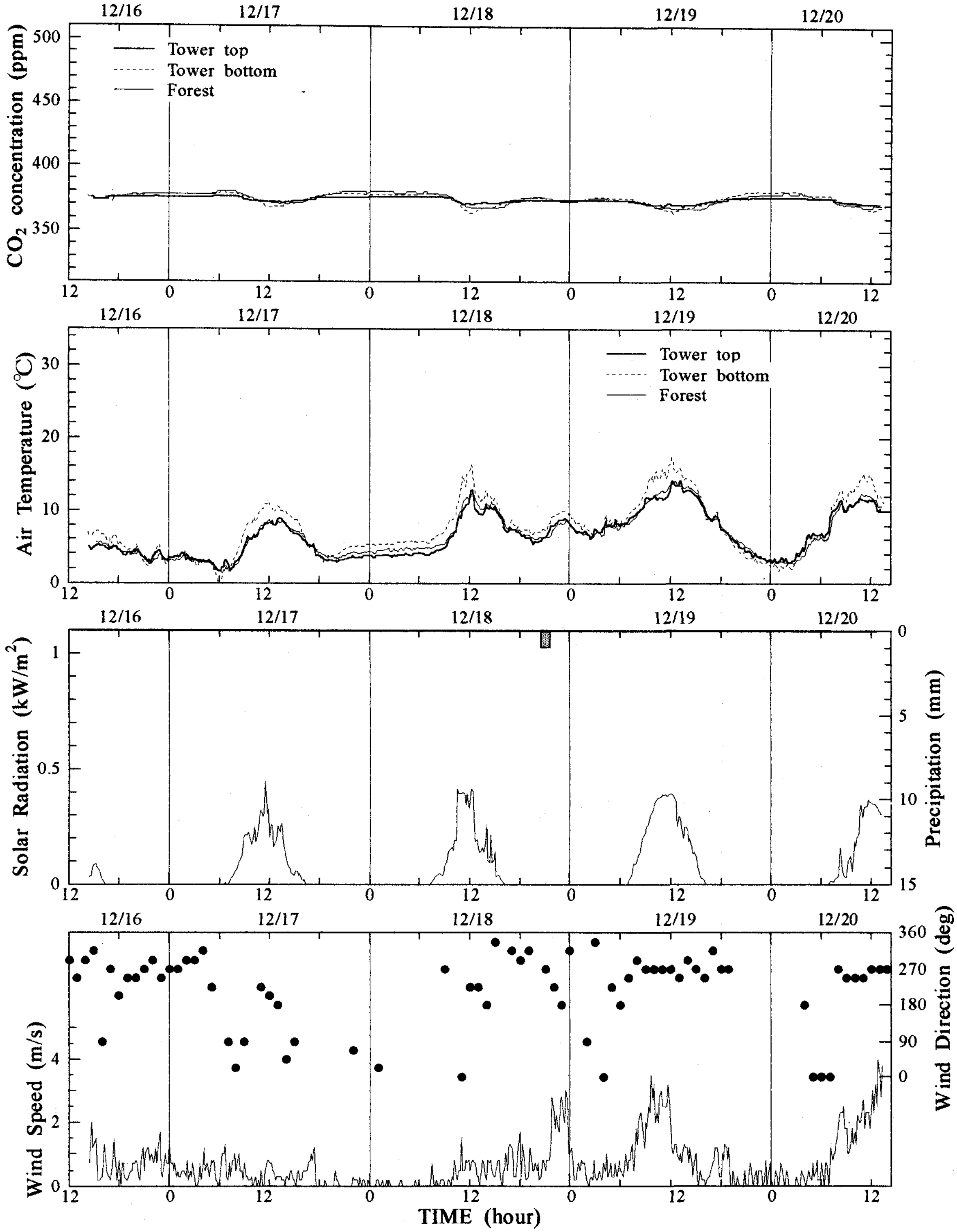

Figure 6. Results: December, 1997

During the measurement in May, the weather was not good except on 16th and the soil surface condition was always wet. It was observed that CO_2 concentration became low in the fine daytime(on 16th). It is because of the photosynthesis of vegetation. In the night, it becomes very high in the vicinity of ground. It represents the respiration of soil. The concentration at the base of tower was higher than at the top in the night. This difference means the upward flux of CO_2. In the daytime, the difference between at the top and the base became reverse. But its amount is not large. The rise of CO_2 concentration is not prominent in the night of 17th. In this night, the temperature was about 10 degree lower than the others. It has been known that the activity of soil respiration increases 2 or 3 times when the temperature rises 10°C. Therefore, the temperature difference of 10°C affects CO_2 variation appreciably.

It was windy in the measurements in July. Therefore, no prominent variation was observed at all points from the afternoon of 4th to the evening of 5th. After wind got weak, CO_2 increased in the night of 5th and decreased in the daytime of 6th.

In September, the activity of both vegetation and soil was still high and the variation of the concentration was prominent even on rainy days(7th and 8th).

In December, almost all leaves fell and the photosynthesis stopped. The respiration of soil also stopped because the temperature was lower than 10°C. Only small variation observed may be due to needle leaved trees mixed in the forest.

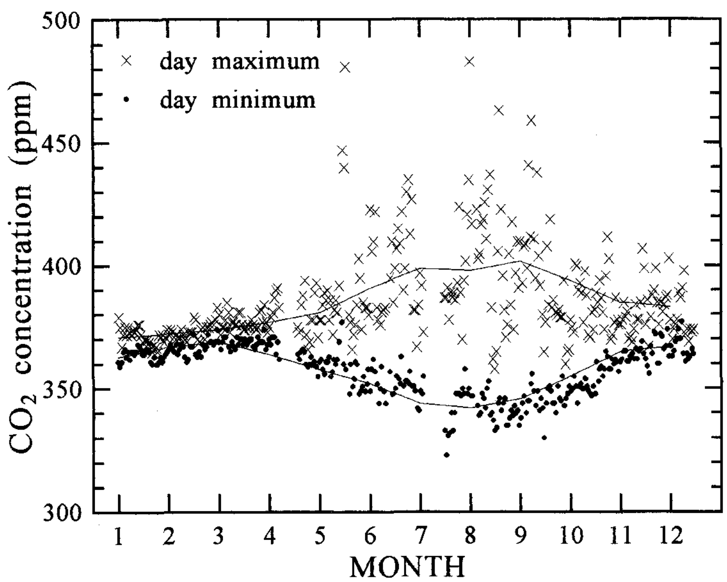

Figure 7. Daily maximum and minimum of CO_2 concentration in the forest: 1997

The result of continuous measurements is shown in **Fig. 7** in which daily maximum and minimum values and thier monthly averaged values in 1997 were shown.

The daily minimum becomes low in summer and high in winter. This variation corresponds to the growth and withering of leaves. The daily maximum values variate violently in summer. This is because the measurements were carried out near ground(about 1m height) so that the soil respiration affect directly on concentration variation. The minimum appears in the daytime

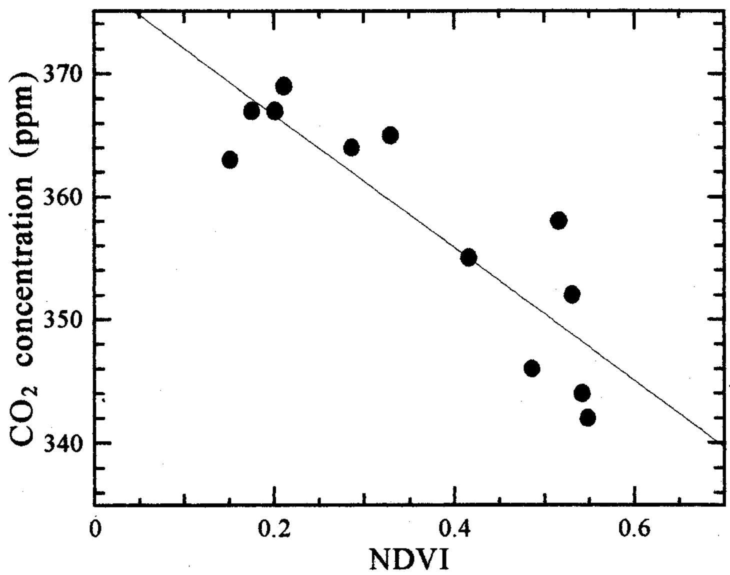

Figure 8. Correlation between NDVI and CO_2 minimum

when the stability of atmoshpere is usually weak. On the other hand the maximum apprears in the night when the stability variates every day so that the maximum variates violently.

Figure 8 shows the correlation between monthly averaged minimum value and NDVI observed NOAA satellite. NDVI is calculated from NOAA-AVHRR data as follows;

$$\text{NDVI} = \frac{\text{Ch.2} - \text{Ch.1}}{\text{Ch.2} + \text{Ch.1}} \tag{1}$$

where Ch.1 is the brightness of visible channel(0.58~0.68μm) and Ch.2 is of near-infrared channel(0.725~1.10μm). The Japan Image Database/N-LAND (JAIDAS/N-LAND:Computer Center, Tohoku University) was utilized. This database serves the dataset of NOAA/AVHRR over land area in fine days after systematic correction. The value at a clear day around 15th of each month is adopted as monthly representative. Because the resolution of NOAA/AVHRR data is about 1.1km and the value of NDVI is affected by local topogtraphy, it is difficult direct comparison at the measuring points of CO_2. Then the averaged value of NDVI for forest about 10km square around Kawatabi is compared with CO_2 measurements. It is clearly observed that the CO_2 minimum decreases as NDVI increases.

3. Model of CO_2 variation

3.1 Modeling

Considering the seasonal differences of vegetation activity and soil respiration, it is tried to explain the daily variation of CO_2 in the forest in this section.

At first, it is assumed that the forest is uniform and the horizontal convection is negligible in the discussion.

Setting a control volume shown in **Fig. 9** and summing up some terms in **Fig. 1**, CO_2 balance in the area A of forest is represented as

$$\frac{dCO_2}{dt} \cdot V = R_{esp} \cdot A - P \cdot LAI \cdot A + k \cdot dCO_2 \cdot U \cdot A \quad (2)$$

where $\frac{dCO_2}{dt}$ is a changing rate of CO_2($mgCO_2/m^3hr$), R_{esp} is soil respiration(R_M in **Fig. 1**) of unit area($mgCO_2/m^2hr$), P is the vegetation activity($P_g - (R_F + R_C + R_U)$) of unit leaf area($mgCO_2/m^2hr$), LAI is Leaf Area Index(m^2/m^2), $P_{act}(= P \cdot LAI)$ is vegetation activity in unit area, k is a coefficient representing a exchange, dCO_2 is the difference of CO_2 concentration between outer atmoshpere and that in the box($mgCO_2/m^3$), U is wind speed(m/s), and A and V are area and volume of the control box. However, the last term will not evaluate quantitatively here.

The following is should be noted. The purpose of modeling is to explain the seasonal difference of **Eq. (2)**. Therefore, each terms in $P(P_g, R_F, R_C$, and $R_U)$ are not evaluated rigorously, but, it is simply assumed that seasonal variation of vegetation activityP_{act} is propotional to LAI and its intensity is tuned so that the annual balance is consistent.

Here, we evaluate R_{esp} and P_{act} through the knowledge on annual and monthly NPP.

Soil respiration is usually represented as a exponential of temperature T as

$$R_{esp} = c \cdot \exp(d \cdot T) \quad (3)$$

It is pointed out that the activity of soil rises from 2 to 3 times when the temperature rises 10°C. Therefore, we assumed d=0.11(1/°C) which corresponds to the value 3. This value is reasonable comparing with Nakane et al.(1984). Temperature T is soil temperatureT_{soil} in the equation. However, only air temperature T_{air} is available. Refering Nakane et al.(1984), the soil temperature was estimated from $T_{soil} = 0.85 \cdot T_{air}$. The coefficient c will be determined from the annual balance of production and respiration afterward.

The vegetation activityP_{act} consists of photoosynthesis and respiration. It is difficult to evaluate them separately. Therefore, following expedient method is adapted.

It is assumed that P is represented similarly to photosynthesis as

$$P = \frac{a \cdot I}{b + I} \quad (4)$$

where I is effective solar radiation for photosynthesis(W/m^2). Refering Sellers et al.(1992) and Potter et al.(1993), it is assumed that I is a half of total solar radiation and the value of b is 300 W/m^2. The coeeficient a is determined to be consistent to the annual NPP mentioned below. The respiration of vegetation is underestimated when in the solar radiation is small. The error of this inaccuracy is corrected by tuning the coefficent c in **Eq. (3)**.

Product of the coefficient a and monthly LAI is calculated as follows.

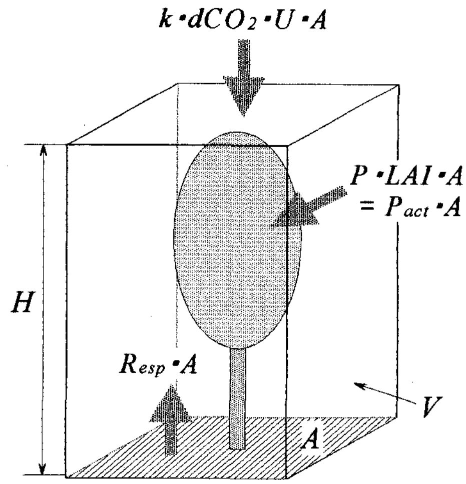

Figure 9. Control box

The monthly NPP in Miyagi Prefecture has been reported by Tada(1998) separately as shown in the column "NPP" of **Table 2**. Integrating $I/(b+I)$ in **Eq. (4)** for each month and equating with the monthly NPP, the monthly variation of $a \cdot LAI$ is determined. The results are shown in the column "$a \cdot LAI$". In this calculation, LAI in winter is set to be zero because NDVI is almost zero in winter.

It is convinient to use NDVI instead of LAI in an application for wide area.

Table 2. Monthly NPP(Tada,1998), $a \cdot LAI$, P_{act} and R_{esp}(kgDW/ha month)

	NPP	$a \cdot LAI$	P_{act}	R_{esp}
Jan	12	0	0	245
Feb	25	0	0	219
Mar	65	0	46	320
Apr	333	560	437	528
May	1,394	1,919	1,287	816
Jun	1,730	2,320	1,731	1,187
Jul	1,805	2,650	1,831	1,793
Aug	2,108	3,260	2,036	1,776
Sep	1,278	3,120	1,172	1,174
Oct	640	1,160	750	684
Nov	218	560	232	482
Dec	28	0	22	320
Sum	9,635		9,544	9,544

The correlation between NDVI and LAI is shown in **Fig. 10** in which the value of LAI is used in **Table 2**. Some formulae for relationships between NDVI and LAI have been reported (Nemani and Running:1989, Fujino et al.:1997). For comparison with those results, it is assumed temporally that the maximum value of LAI is 7 and $a = 465$ $mgCO_2/m^2hr$ in this figure. But, the direct correlation indicated in **Eq. (8)** will be used in the model.

If we further assume that the forest is grown enough, a climax forest, where annual amount of photosynthesis is balanced with annual decomposition and respiration and no accumulation of carbon occurs annually, P_{act} balances with total annual litter fall($L_F+L_C+L_U$) and annual soil respiration R_{esp} also balances with total litter fall. Finally, NPP, P_{act}, balances with soil respiration annually as

$$P_{act:year} = R_{esp:year} = \int_{1year} (c \cdot \exp(d \cdot T))\, dt \tag{5}$$

The coefficient c in **Eq. (3)** was tuned from this relationship.

The various units are used in above mentioned equations. Converting all units to $mgCO_2/m^3$, finally following equations were derived.

$$P_{act} = \frac{0.5S}{300 + 0.5S} \cdot a \cdot LAI \tag{6}$$

$$R_{esp} = 47.8 \cdot \exp(0.11 \cdot 0.85T_{air}) \tag{7}$$

$$NDVI = 0.14 \cdot ln(a \cdot LAI) - 0.28 \tag{8}$$

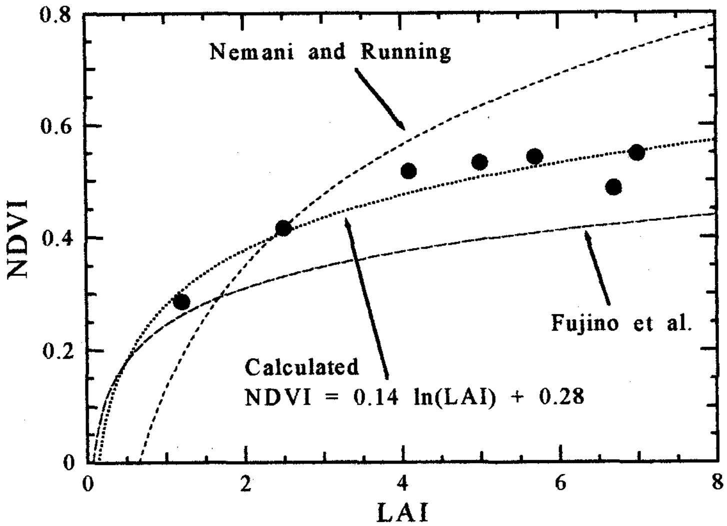

Figure 10. Relationship between LAI and NDVI

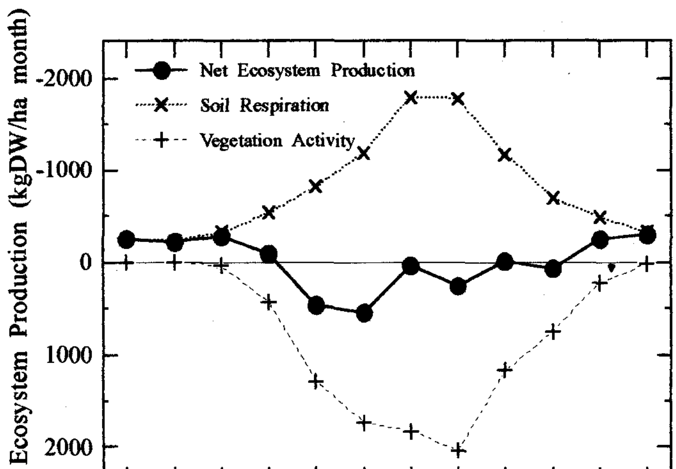

Figure 11. Monthly variation of Vegetation Activity and Respiration

where, S is total solar radiation(W/m^2), T_{air} is air temperature(°C).

Although some assumptions were introduced in the derivation of those equations, those make possible to evaluate the soil respiration and vegetation activity in deciduous forests only from the air temperature, solar radiation and NDVI observed by satellites.

The monthly variation of vegetation activity and soil respiration calculated from those equation are shown in **Table 2** and **Fig. 11**. In the figure, the difference between production and soil respiration is also shown. This corresponds net production of the ecosystem. Although both the production and the respiration become large in summer, the net prodution is positive from April to October. Annual net production is nil because of assumption in the modeling. This results is almost similar as the results of deciduous forest in the Temperate Zones reported by Fung et al.(1987).

3.2 Calculation of the model

Instead of **Eq. (2)**, we calculate following equation, because we have not modeled the last term of **Eq. (2)**.

$$\frac{dCO_2}{dt} \cdot V = R_{esp} \cdot A - P \cdot LAI \cdot A \tag{9}$$

In other words, the purpose of this comparison is not to discuss the total applicability of model but to discuss the effects of each terms in **Eq. (2)**.

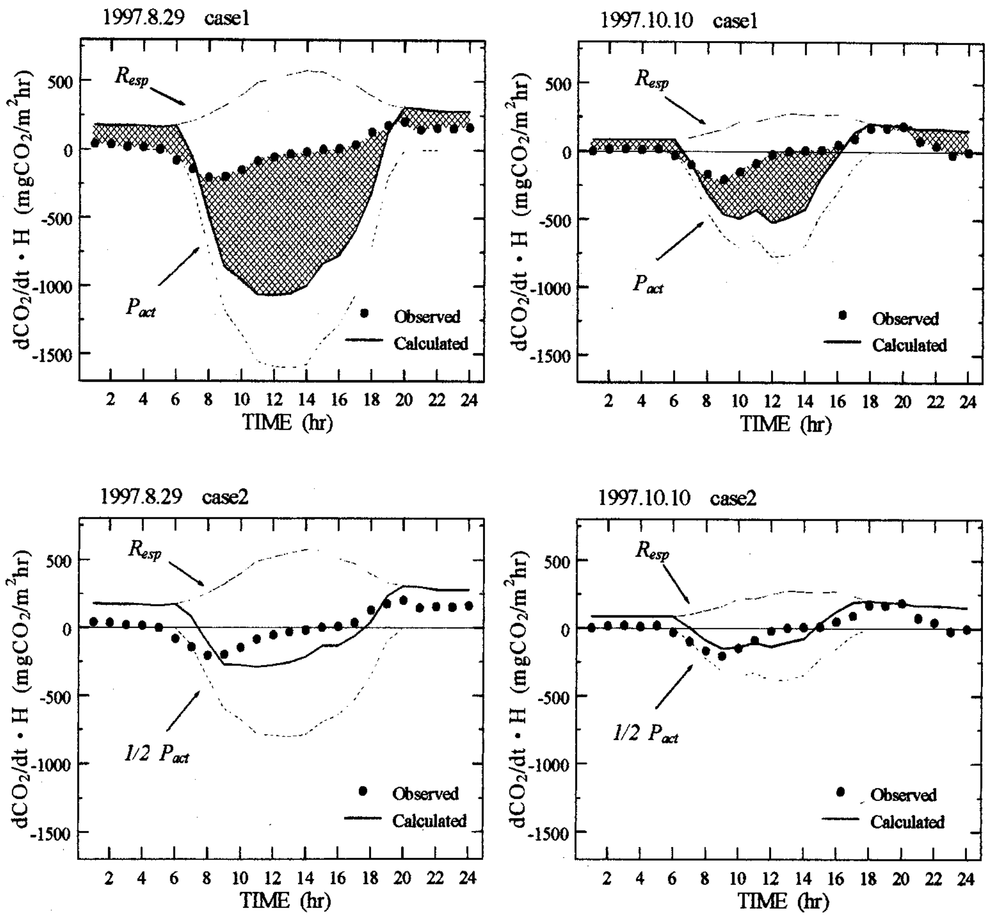

Figure 12. Comparison between the model and observations

Comparisons of **Eq. (9)** with measured $\frac{dCO_2}{dt}$ in summer and autumn are shown in **Fig. 12**. NDVI of the season obtained at Tohoku University, total radiation measured by Agricultural Center which is located about 20km far from Kawatabi and air temperature of AMeDAS are used in the calculation. The height of control box is set to be 10m which is average height of the forest.

The upper figures, which refered Case 1, show direct comparisons of **Eq. (9)** with the observations. It is obvious that the agreement is not good. The magnitude of P_{hot} is to be almost twice of R_{esp} and the net production becomes very large. This tendency is calculated in almost all seasons.

This may be explained in two ways.

The first explanation is that the discrepancy between the model and observations means the effect of the last term in **Eq. (2)**. In this explanation, the shaded part in the figure represents the CO_2 flux from/into the control box. It becomes negative in daytime and positive in night. This fact is consistent to the function of forest on CO_2 cycle.

In the second one, a part of discrepancy is attributed to incompleteness of the model. The uniformity of CO_2 concentration in the box is assumed in modeling.

Acctually, it variates from point to point in the box. It is rather high in the vicinity of ground and low in the mass of leaves. The screen is set at 1m height so that the CO_2 meter is more sensible to R_{esp} than P_{act}. Further, the leaves at the upper surface of the control box may directly fix CO_2 outside of the box and have no effect onto the CO_2 concentration in the box.

The results of second explanation is shown in the lower figures(case 2), where it is temporally assumed that a half of P_{act} was measured by the meter. Although it is unknown which explanation is more reasonable, the second one gives better agreement apparently. **Fig. 13** shows the long term application of the model in case 2. The tendency of seasonal variation is represented well. However, the calculation is little bit larger than the observations in winter because NDVI is assumed nil in winter. In summer, both the calculation and observation variate violently. It is confirmed that the agreement is better in fine days than clouded or rainy days. The activity of forests decreases in autumn both in the observation and the calculation.

Although the activity of vegetation is complicated, the model propose here is rather simple. However, the tendency of CO_2 variation is represented well.

4. Conclusions

In order to understand the role of forests on CO_2 variation, firstly some series of measurements were carried out in a deciduous forest. Although it is known that CO_2 in upper atmosphere decreases in summer and increases in winter because of seasonal variation of photosynthesis, the results of measurements show that CO_2 concentration variates violently in summer and the maximum is also observed in summer.

Secondly a model was proposed to describe the observations. The coefficients were determined so that the model was consistent with the satellite observed vegetation activity and NPP evaluated on the ground. Although the model is simple, the fundamental feature of CO_2 variation is represented.

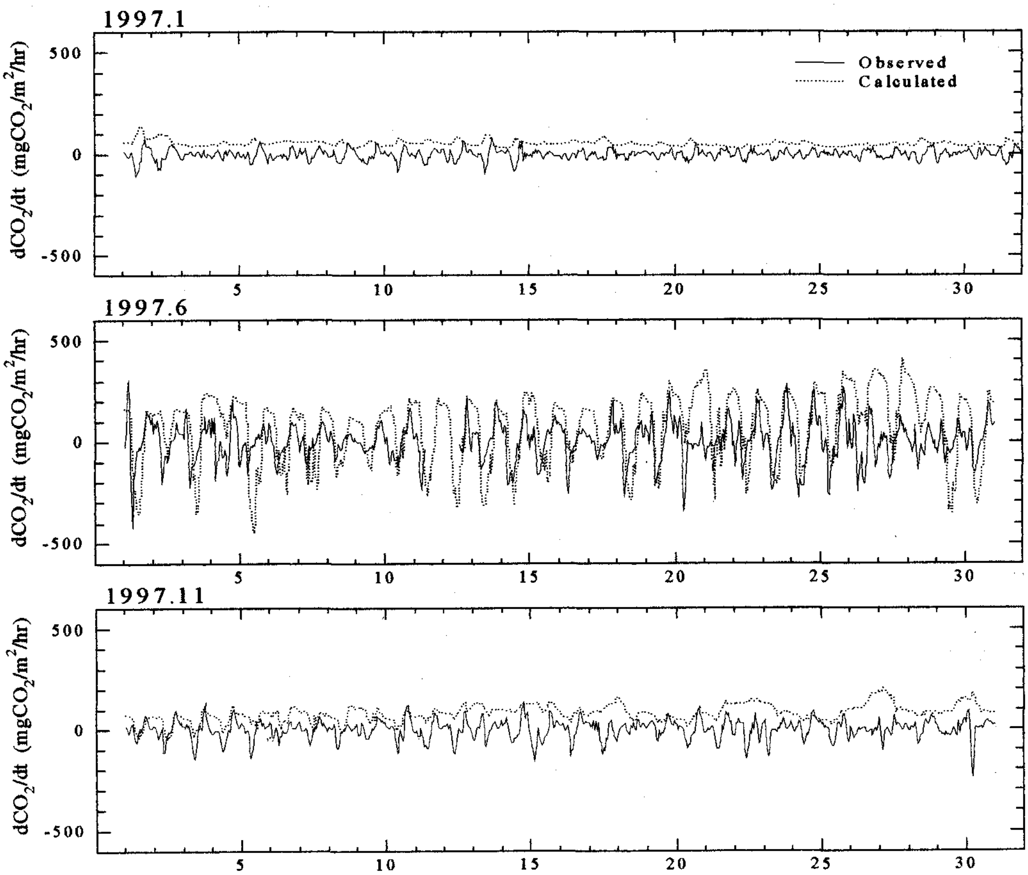

Figure 13. Comparison of Case 2 in January, June and November

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