MEASUREMENT OF GRADIENT OF CARBON DIOXIDE AND ESTIMATION OF ITS FLUX OVER A PADDY FIELD (2) OBSERVATION AT HACHIHAMA IN 1969

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INTRODUCTION

In the earlier paper (Ohtaki and Seo, 1972), some characteristics of diurnal and seasonal variation of CO_2 gradient over a paddy field have been elucidated by the data obtained at Kurashiki in 1968. It was attempted also to estimate the CO_2 flux by the aerodynamic method as developed by Inoue et al. (1957, 1958) and confirmed by a number of workers (Lemon, 1960; Monteith, 1962; Denmead, 1968; and Yabuki and Ishibashi, 1968).

The Kurashiki site was situated in an urban district and had a rather limited area (120 m$\times$120 m). The measurements were carried out at relatively low levels and measuring masts were positioned to make the fetch maximum for the prevailing wind directions. It was felt, however, necessary to duplicate the similar observation on a site satisfying more adequately the fetch requirement. A suitable site was found in the University Farm at Hachihama, and observations were carried out during July to October in 1969.

METHODS

Site

The experimental farm was located on a reclaimed land at the distance of about 20 km southeast of the Kurashiki site. The general topographic aspects of the Hachihama site can be seen from the map given in an earlier paper (Seo et al., 1972). The measuring masts were positioned on the field as indicated in Fig. 1. The prevailing winds were southerly in daytime and northerly at night. Thus the storehouse to the west presented no serious obstacle to the measurements.

The paddy seed (Akebono) was drilled in the middle of May at the rate of 80 liters per hectare in SE-NW rows 30 cm apart. The paddy crop germinated around May 20 and came into ears during late August to early September.

The field was irrigated during July to September in a regular weekly cycle: irrigation was started on Tuesday and ended on Friday.

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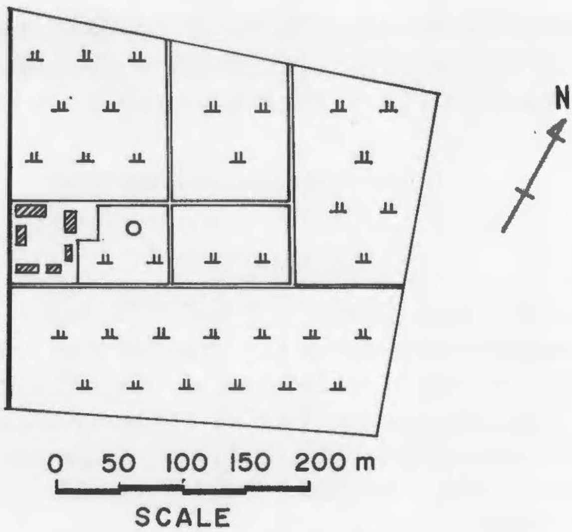

Fig. 1. Experimental Farm of Okayama University at Hachihama. Measuring position is marked by circle. Shading areas indicate storehouse, garage, and laboratory.

Equipment

The measuring method and the data-processing procedure were generally the same as used in the Kurashiki observation in 1968. Some modifications and additions made in the Hachihama observation will be described below.

CO_2 *Gradient* A gas sampling system was constructed to measure the CO_2 difference for two height intervals 30–60 cm and 60–120 cm above the crop. Air sampled at each level of 30, 60 and 120 cm was sequentially passed through the sample cell at intervals of 2 min, while the reference cell was continuously flushed with the air from 60 cm level. The time constant of the gas interchange system was approximately 45 sec and the recorded point at 1 min after each change-over signal was read. Hourly means of CO_2 difference ΔC were constructed for height intervals 120–60 cm and 60–30 cm from 10 readings during one hour. The plot of ΔC (120–60 cm) against ΔC (60–30 cm) showed considerable scatter presumably due to error involved in the sampling procedure, and the difference of CO_2 between 120 cm and 30 cm was used in calculating the flux. The sensitivity of the analyzer URAS 2 was found to remain practically unchanged from that in the Kurashiki observation: about 2 mm deflection per 1 ppm on a potentiometric recorder of the range 0–5 mV.

CO_2 *Concentration* For the last three observations (Aug. 28– Sept. 4, Sept. 28– Oct. 1, Oct. 8– 11), the profile of CO_2 concentration above and within the crop stand was examined with use of a Beckman gas analyzer. The air through the sample cell was interchanged between 6 different air paths at 1 min interval in 6 min cycle. The analyzer was operated with the full scale of 0-600 ppm. The sensitivity of the analyzer was not linear in CO_2 concentration and for the normal atmospheric concentration the variation of 10 ppm in CO_2 concentration yielded 2 mm deflection on the recorder chart. The hourly mean for each level was derived from the average of 10 readings during one hour period.

Wind Speed Wind speeds were measured at five heights of 30, 60, 120, 240, and 480 cm above the crop with SANOYA cup anemometers. Anemometers were mounted on a measuring mast with arms of 50 cm length. A thermistor anemometer was mounted at 60 cm above the crop to ensure the data acquisition under circumstances of low wind speeds. The anemometers employed were standardized by means of a whirling arm of 1 m length before and after each observation.

Air Temperature Air temperature was measured at 30 cm and 240 cm above the crop with a copper-constantan thermocouple equipped with a simple radiation cover. The output of the thermocouple was recorded on a self-balancing potentiometer of full scale 1.5 mV. Hourly mean of air temperature was constructed from the readings at 5 min intervals. Air temperature data were used in the calculation of Richardson number in the air layer over the crop.

Method of Calculating CO_2 *Flux*

The vertical flux of CO_2 can be written in the form

$$F_{CO_2} = (C_1 - C_2) \Big/ \int_{z_1}^{z_2} \frac{dz}{K_m}, \qquad (1)$$

where F_{CO_2} is the vertical flux of CO_2, $(C_1 - C_2)$ is the difference of CO_2 concentration between two heights z_1, z_2, and K_m is the eddy diffusivity for momentum. The transport coefficient for momentum $1 \Big/ \int_{z_1}^{z_2} \frac{dz}{K_m}$ is determined from wind profiles by the method suggested by Panofsky (1963); the wind profile representation used is KEYPS for unstable cases and the log-linear representation for stable cases (Webb, 1970).

After Panofsky the diabatic wind profile is given by the formula with usual symbols

$$u = \frac{u_*}{k} \left[\ln\left(\frac{z-d}{z_0}\right) - \psi\left(\frac{z-d}{L'}\right) \right], \qquad (2)$$

where $\psi\left(\frac{z-d}{L'}\right)$ is related to a universal function $\phi\left(\frac{z-d}{L'}\right)$ by

$$\psi\left(\frac{z-d}{L'}\right) = \int_0^{\frac{z-d}{L'}} \frac{1-\phi(\xi)}{\xi} d\xi \quad , \qquad (3)$$

and L' is defined by

$$L' = u_* T \frac{\partial u}{\partial z} / gk \frac{\partial \theta}{\partial z} \ . \quad (4)$$

Deriving the transport coefficient for momentum $1 \Big/ \int_{z_1}^{z_2} \frac{dz}{K_m} = u_*^2 / \Delta u$ from Eq. (2) and substituting it into Eq. (1), we have a formula for evaluating CO_2 flux:

$$F_{CO_2} = k^2 (C_1 - C_2)(u_2 - u_1) \Big/ \left[\ln\left(\frac{z_2-d}{z_1-d}\right) + \psi\left(\frac{z_1-d}{L'}\right) - \psi\left(\frac{z_2-d}{L'}\right) \right]^2 \ . \quad (5)$$

Some remarks about the computational procedure are added. Richardson number Ri is calculated from differences in air temperature and wind speed between two heights z' and z'' above the ground. The Ri-number gives the corresponding value of $(z-d)/L'$ by the functional relationship $(z-d)/L' = Ri/\sqrt[4]{1-18Ri}$ in unstable cases and $(z-d)/L' = Ri/(1-5Ri)$ in stable cases; $(z-d)$ is taken equal to $(z'-z'')/\ln\left(\frac{z'-d}{z''-d}\right)$. Best fit to the linear plot: u_i vs. $\ln(z_i-d) - \psi\left(\frac{z_i-d}{L'}\right)$ determines the value of d. u_* is obtained as the slope of the fitted straight line, and wind difference (u_2-u_1) is read from the adjusted profile.

RESULTS AND DISCUSSION

Diabatic Effect in the Calculation of CO_2 *Flux*

In the present observation, wind measurements up to 480 cm were utilized in the profile analysis, and the assumption of neutrality had to be discarded. The importance of diabatic correction was further emphasized by the climatological characteristics of the district: through the observation period, wind speeds were frequently low under intense solar radiation.

Fig. 2 (Aug. 20) illustrates a typical but a somewhat extreme case. The weather was generally fair in the period, though cloud development in the afternoon led to decrease in net radiation. Wind speed at 240 cm above the crop was lower than 1 m s^{-1} in the morning, remained at about 1 m s^{-1} during the midday hours, and became moderate in the late afternoon. Wind difference ΔU between 240 cm and 30 cm above the crop was only 20 to 30 cm s^{-1} in the morning and did not exceed 100 cm s^{-1} until late afternoon. The difference of air temperature ΔT between 240 cm and 30 cm above the crop was negative, i.e. the stratification was in lapse, during the period 7-15 hr. In the period 8-14 hr it varied within narrow limits 0.5-0.8 °C with a maximum between 9 hr and 11 hr. The variations in ΔU and ΔT indicate that the diabatic effect

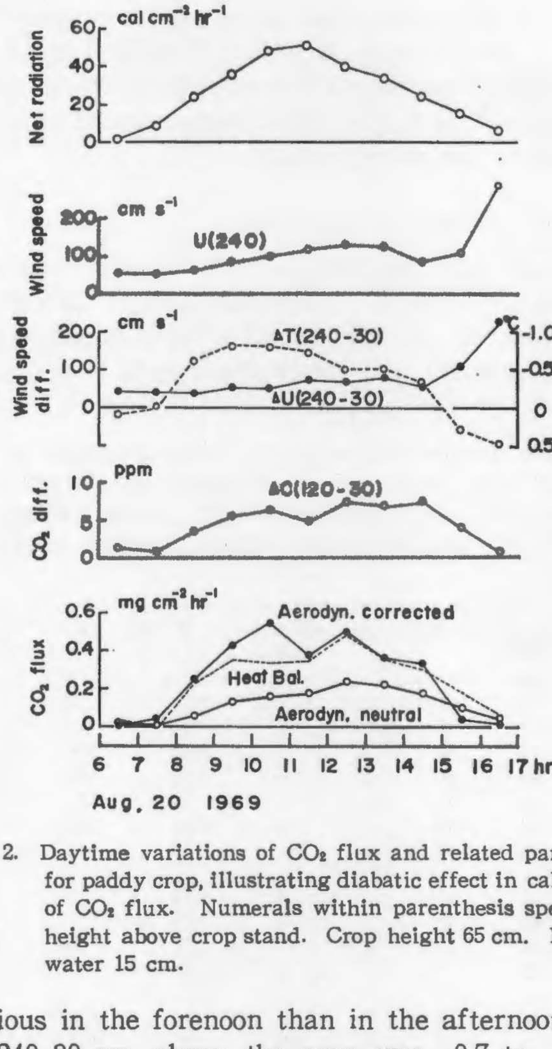

Fig. 2. Daytime variations of CO_2 flux and related parameters for paddy crop, illustrating diabatic effect in calculation of CO_2 flux. Numerals within parenthesis specify the height above crop stand. Crop height 65 cm. Depth of water 15 cm.

was more serious in the forenoon than in the afternoon; calculated *Ri*-number for 240-30 cm above the crop was -0.7 to -1.3 in the period 8-11 hr and decreased in magnitude to -0.2 to -0.4 in the subsequent hours of 11-15 hr.

In the bottom figure CO_2 flux calculated by the present method (aerodynamic corrected) is compared with that calculated on the assumption of neutral equilibrium (aerodynamic neutral). The figure shows that the neglect of diabatic effect leads to appreciable underestimate of the flux during most of the daylight hours. The daytime variation of CO_2 flux followed broadly the net radiation pattern and the flux corrected for the stability effect showed a fairly good agreement with the flux calculated by the heat balance method (Seo and Ohtaki, 1974).

It must be noted that the effect of water vapor on air density was neglected in the calculation of *Ri*-number. Sample calculations indicated that the inclusion of water vapor effect could increase the calculated daytime flux up to 30 per cent in hourly value and up to 15 per cent in daily total. However, consistent exact calculation of *Ri*-number was impracticable, since sufficiently reliable measurements of humidity gradient were not available in the present study.

Seasonal Variation of Daytime CO_2 *Flux*

Table 1 contains daytime totals of CO_2 flux, and daytime means of CO_2 difference and wind speed. It also summarizes the surface conditions during the observational periods: height of crop stand, daytime averages of zero-plane displacement and roughness length, and depth of water.

TABLE 1. Daytime downward flux of CO_2, F_{CO_2}, calculated by aerodynamic method with daily values of related parameters. d=zero-plane displacement; z_0=roughness length; S=net radiation; U=wind speed; ΔC=CO_2 difference between specified heights above crop stand.

Hachihama		Crop height cm	d cm	z_0 cm	Water depth cm	S cal cm^{-2}	U 120cm cm s^{-1}	ΔC 120-30cm ppm	$-F_{CO_2}$ mg cm^{-2}
1969	hr								
July	19 (5-19)	40	30	2	3	346	166	2.0	1.3
	20 (6-18)	40	30	3	2→1	351	151	2.5	2.4
	27 (〃)	50	40	3	1	339	122	2.8	1.4
	28 (7-18)	50	40	3	0	389	152	3.1	1.3
	29 (6-18)	50	40	3	2→13	422	183	2.6	1.1
Aug.	16 (6-18)	65	45	5	0	414	125	3.5	3.2
	17 (7-17)	65	45	6	0	371	137	4.1	3.3
	20 (6-17)	65	45	4	15	276	95	4.5	2.9
	30 (7-17)	75	*	*	0	206	*	3.9	*
Sept.	3 (6-18)	75	50	7	12	244	121	4.3	4.4
	17 (7-17)	100	*	*	15	155	144	2.2	*
	18 (6-17)	100	*	*	15	343	112	2.4	*
	19 (7-17)	100	*	*	2→0	310	95	2.8	*
	29 (〃)	95	55	9	0	186	164	2.7	2.1
	30 (〃)	95	*	*	0	*	115	2.2	*
Oct.	9 (7-16)	90	55	6	0	272	324	1.3	1.2
	10 (7-17)	90	55	6	0	149	142	1.1	0.5

In the Kurashiki observation the daytime totals of downward CO_2 flux, i.e. net photosynthesis of the crop minus soil CO_2 emission, showed a seasonal dependency on the crop growth. From the results in Table 1 above and Table 2 of the earlier paper, Fig. 3 has been constructed to show the seasonal variation of daytime CO_2 flux over the paddy crop in our district. As can be seen from the figure, daytime totals in Hachi-

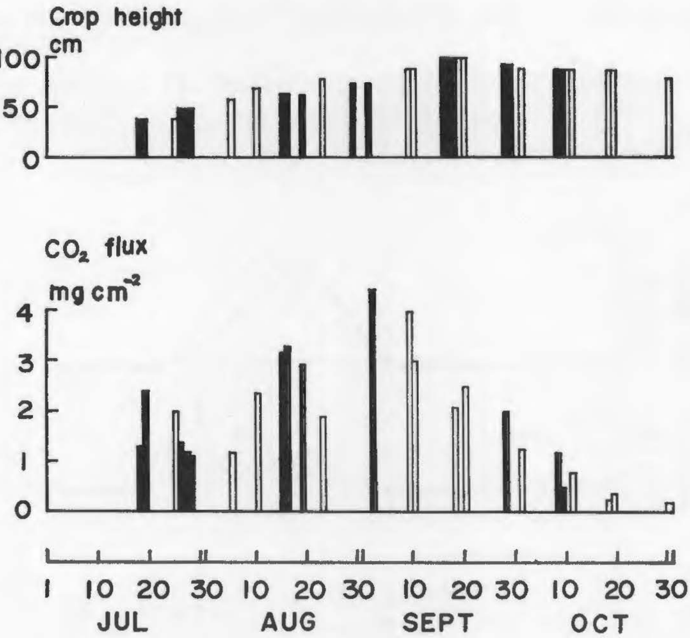

Fig. 3. Seasonal variation of daytime totals of CO_2 flux over paddy fields and seasonal change in height of paddy crop. Solid bar: Hachihama in 1969. Open bar: Kurashiki in 1968.

hama and Kurashiki observations showed in general a similar seasonal trend. The compatibility between flux values at these two sites indicates that the urban effect at the Kurashiki site was not serious in the 1968 observation at least for the daytime period.

Daytime total of downward CO_2 flux was 1 to 2 mg cm^{-2} in the last decade of July, increasing to 2 to 3 mg cm^{-2} in the middle of August; during this period the crop height increased from 40 to 70 cm. The flux attained a maximum value of 3 to 4 mg cm^{-2} during late August to early September, by which time the crop had come into ears. The efflorescence occurred about a week later than the ear emergence. As the paddy crop entered into the yellow ripening stage in late September, the flux decreased rapidly, and it was reduced to about 0.5 mg cm^{-2} or less at the harvest time.

The figure shows further that CO_2 flux on individual days, occasionally, deviated appreciably from the general seasonal trend. The values of CO_2 flux on Aug. 6 and Aug. 24, 1968 were low compared with those on the neighboring days; these low values were associated with the lower levels of net radiation (cf. Table 2 in Ohtaki and Seo, 1972). Relatively low values of flux in the period July 27-29, 1969 have not been explained as yet.

Diurnal Variations of CO_2 Gradient over Drained Field and Submerged Field

Fig. 4 illustrates the diurnal variation of CO_2 gradient and related parameters. Data of Aug. 16/17 and Aug. 19/20 refer to a drained period and to a submerged period respectively.

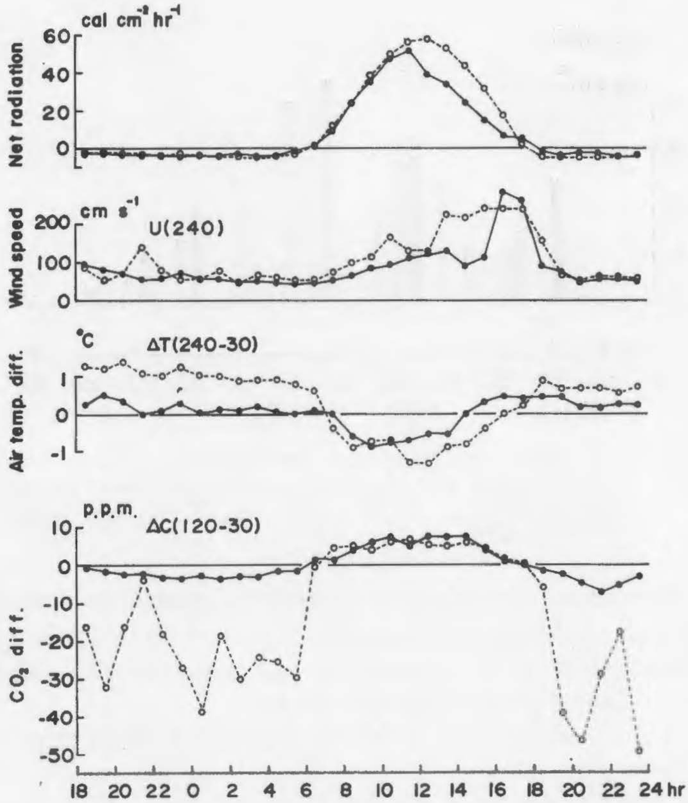

Fig. 4. Diurnal variation of CO_2 difference over drained field and submerged field, together with variations of net radiation, wind speed, and air temperature difference. Numerals within parenthesis specify the height above crop stand. Crop height 65 cm. Dashed line: drained period, August 16/17 in 1969. Full line: submerged period, August 19/20 in 1969.

Daytime variations in CO_2 gradient were similar on the submerged field and drained field; the CO_2 difference between 120 cm and 30 cm above the crop varied between rather narrow limits (5 and 7 ppm) except transition periods. At night, however, CO_2 gradient above the crop depended markedly on the surface condition of the ground. While on the submerged field, the CO_2 gradient maintained relatively small and steady values (generally less than 5 ppm/90 cm), the gradient on the drained field was large and variable, notwithstanding the wind speed was in general slightly higher in the drained period.

Exceedingly large CO_2 gradient of 30 to 50 ppm/90 cm was built up under light wind conditions. It is remarkable that the increase in wind speed during 21-22 hr on Aug. 16 brought about marked reduction in CO_2 gradient to 4 ppm/90 cm. It can be concluded that the similar phenomena noted at the Kurashiki site in 1968 have been confirmed in the present observation.

The third figure from the top shows that the temperature gradient in the air layer above the crop appeared different between drained field and submerged field. Nocturnal inversion of air temperature was built up more effectively on the drained field than on the submerged field. It is probable that the intense stability over the drained field contributed significantly to the large CO_2 gradient encountered there. The earlier transition from lapse to inversion regime of air temperature on Aug. 20 (submerged period) is associated with the decrease in net radiation in the afternoon.

CO_2 *Profile on Paddy Field*

In the preceding sections only CO_2 gradient and atmospheric CO_2 flux at one level above the crop have been discussed. A complete description of CO_2 balance of the crop stand requires the knowledge of profiles of CO_2 concentration and eddy diffusivity through the crop stand.

In Fig. 5 CO_2 profiles within and above the crop are illustrated for drained period (Aug. 29/30) and for submerged period (Sept. 2/3). The paddy plant was 75 cm in height during the observation periods.

During the night of Aug. 29/30 a steep CO_2 gradient indicating upward flux prevailed through the stand. Concentration as high as 550 ppm was found at the lower levels near the surface (Aug. 30, 01-02 hr). This large nocturnal CO_2 accumulation within the vegetation was observed also in a corn field (Allen, 1971). The large gradient and concentration were resolved intermittently by slight increase in wind speeds. The steep gradient that prevailed at night was quickly dissipated in the morning, and during daylight hours a zone of active assimilation appeared as CO_2 minima in the middle to upper layer of the stand.

On Sept. 3 the daytime vertical distribution of CO_2 concentration was broadly similar to that on Aug. 30. In contrast, the CO_2 distribution during the night Sept. 2/3 was significantly different from that on the night Aug. 29/30. It can be seen that the gradient was reduced and the concentration was decreased on the submerged field as compared with those on the drained field. It is remarkable that the highest zone of CO_2 concentration tended to occur in the middle layer of the stand

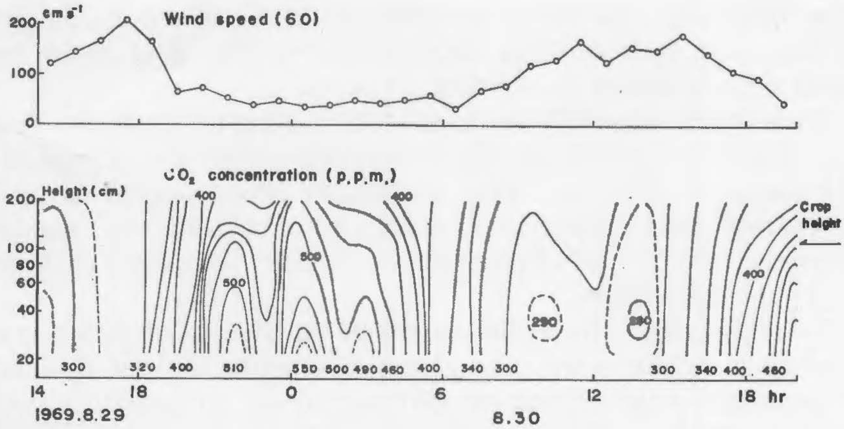

Fig 5 (a). Profile of CO_2 concentration within and above paddy crop for drained period, and wind speed measured with thermistor anemometer at 60 cm above crop stand. Crop height 75 cm.

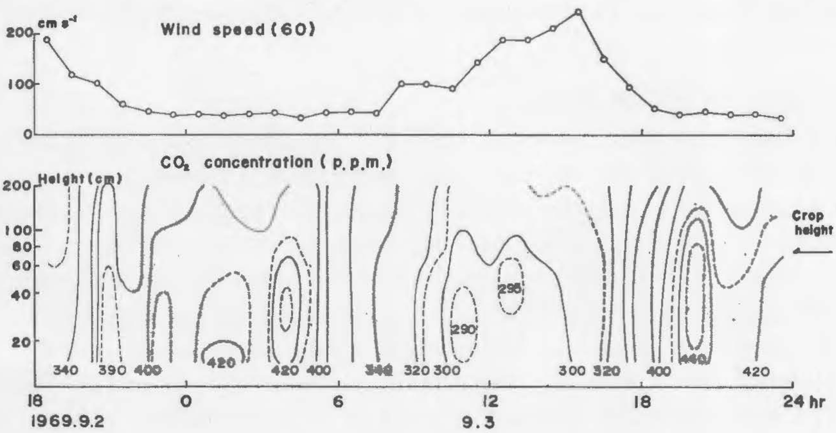

Fig. 5 (b). Profile of CO_2 concentration within and above paddy crop for submerged period, and wind speed measured with thermistor anemometer at 60 cm above crop stand. Crop height 75 cm. Water depth 12 cm.

on the submerged field (Sept. 3, 04 hr and 20 hr). This feature permits us to suppose that the water layer inhibited the CO_2 emission from the soil.

It is of some interest to examine the CO_2 profile on rainy days. Fig. 6 presents the data for such period. CO_2 profile characteristic of daytime was maintained prior to the beginning of rain at 14 hr. With the beginning of rain the CO_2 minimum in the upper layer of the stand disappeared and nearly uniform distribution was established from the surface to above the crop.

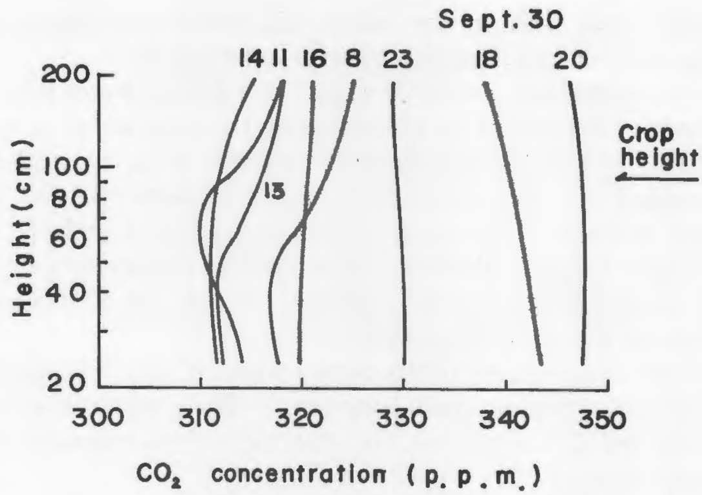

Fig. 6. Profile of CO_2 concentration within and above paddy crop on rainy day, averaged over one hour beginning at the indicated hour of the day. Crop height 95 cm.

Estimate of Nocturnal CO_2 Flux

Weak winds at night present difficulties to the aerodynamic estimate of nocturnal CO_2 flux particularly under strong stable conditions. The difficulties consist not only in the principle (flux-gradient relationship not well founded and similarity between K_m and K_{CO_2} becoming more

TABLE 2. Nocturnal upward flux of CO_2, F_{CO_2}, calculated by aerodynamic method with neutral assumption during submerged periods and nighttime values of related parameters. d=zero-plane displacement; z_0 =roughness length; S=net radiation; U=wind speed; ΔC=CO_2 difference and ΔT=dry-bulb temperature difference between specified heights above crop stand.

Hachihama	Crop height	d	z_0	$-S$	U** 60cm	ΔC 120-30cm	ΔT 240-30cm	F_{CO_2}
	cm	cm		cal cm^{-2}	cm sec^{-1}	ppm	°C	mg cm^{-2}
1969 hr								
July 18 (19-05)	40	30	2	44	58	1.8	***	0.3
19 (19-06)	40	30	2	60	68	3.0	0.3	0.6
29 (18-07)	50	40	3	43	46	2.5	0.1	0.3
Aug. 19 (18-06)	65	45	4	51	32	2.4	0.2	0.3
20 (17-07)	65	45	4	25	38	3.2	0.3	0.5
Sept. 2 (18-06)	75	50	7	28	66	4.9	0.3	1.4
3 (18-07)	75	50	7	18	37	5.6	0.3	1.3
16 (18-07)	100	60*	8*	32	109	0.9	0.5	0.5
17 (17-06)	100	60*	8*	49	36	2.6	0.3	0.6
18 (17-07)	100	60*	8*	60	17	5.7	0.6	0.6

* Estimated value.
**Wind speed measured by thermistor anemometer.

questionable), but also in the measuring technique (impracticability of measuring reliable wind profile by cup anemometer).

As was mentioned above, however, the formation of intense temperature inversion tended to be prevented by the presence of standing water on the field. Thus the aerodynamic method with neutral assumption can be applied for the tentative estimate of nocturnal CO_2 flux during submerged periods. Ten such nights are selected and the results are given in night total in Table 2. The method of calculation is the same as in the Kurashiki observation except for the use of d-value obtained for daytime of the individual days.

The calculated values of nocturnal upward CO_2 flux varied between 0.3 and somewhat higher than 1 mg cm^{-2}. Since water cover practically shielded the soil CO_2 evolution, the obtained values represent the respiration of crop tops.

CONCLUSION

Gradient of CO_2 and other parameters involved in the calculation of CO_2 flux were measured in a paddy field in a rural area Hachihama in 1969.

1) The observed results of CO_2 gradient at Kurashiki site in 1968 were found to be compatible with the results obtained from the present observation. In particular, it was confirmed that nocturnal CO_2 gradient was large and variable on the drained field in contrast to the relatively small and steady gradient over the submerged field. Daytime CO_2 gradient showed a similar pattern irrespective of the surface condition of the ground.

2) For the daytime period, wind measurments up to 4.8 m above the crop were included in the profile analysis; this necessitated the application of Panofsky method in computing the eddy transport coefficient. The results of the analysis demonstrate that the use of neutral assumption requires careful examination of its applicability; otherwise, it could lead to significant underestimate of daytime total and to spurious diurnal variation of the CO_2 flux.

3) Daytime totals of CO_2 flux showed a seasonal dependency on the crop growth, which was well established by Hachihama and Kurashiki observation. It increased with the crop development during the earlier stage of growing season, attained a maximum of about 3 to 4 mg cm^{-2} in the period of ear formation and decreased through the mature stage.

4) The normal summer profile for CO_2 in daylight hours showed concentration minima in the middle to upper layer of the stand. The nocturnal CO_2 concentration tended to show maxima in the middle layer of crop stand in the submerged period.

5) Night totals of upward CO_2 flux estimated for submerged period ranged from 0.3 to 1.4 mg cm^{-2}. The results obtained may be taken as indicating the respiration rate of paddy plant.

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