Journal of Environmental Sciences Vol. 5, No. 4, pp. 470–480, 1993 ISSN 1001-0742

Field carbon dioxide flux density*

Yu Huning

Institute of Geography, Chinese Academy of Sciences,
Beijing 100101, China

Abstract— A synchronous observation of field microclimate parameters using a method of infrared analysis with additional air channel and circuit systems is introduced in this paper. The concentration and the flux density of CO_2 in wheat field and maize field were studied. The data in several years were calculated using aerodynamic method and satisfactory results were obtained. Relation of CO_2 flux to global radiation, net radiation, turbulent exchange coefficient and wind velocity were also analyzed and discussed integrated with practical aspects.
Keywords: CO_2 flux density; CO_2 concentration; wheat field; maize field; microclimate method.

1 Design of experiments and observation

Since 1981 we have been studying techniques monitoring of CO_2 concentration and flux density in fields. The instrument is a non-dispersive infrared CO_2 analyzer (NDIR), which is universally utilized by the basic CO_2 concentration observation stations. There are different types of NDIR. The machine which we used is a QGS-08 infrared CO_2 analyzer (Beijing Analytical Instrument Factory, Maihak Company of Germany). CO_2 concentration in air was measured within the range of 0−500 ppm, and its difference was measured within the differential range, i. e. 0±50 ppm.

Functions of the host instrument and its additional systems should be strictly content with a series of conditions of the research. Firstly, it should be stable and dependable. Its functions should be tested repeatedly in order to check whether its sensibility and stability meet the requirements of analysis, and can detect trivial difference of CO_2 concentration near the canopy. The zero point and sensitivity were identified usually using the standard gas bottle during observational period. It should be washed with strong air flux for several minutes, and then the sample was tested at 0.5 L/min stable flux.

* This project is supported by National Natural Science Foundation of China

To ensure reliability of observation data, air samples should be transferred from specific positions of outside field and the air channels should be sealed strictly to avoid leakage. Effects of fluctuating humidity, temperature and pressure on the sample, effects of CO_2 fluctuating concentration to zero point in the sample should be eliminated. Effect of unstable voltage and current harmonic oscillation on the sensing system must be eliminated. Dust and other materials should be filtered out completely. For these reasons, an air channel system was designed and set up. To reduce the possible measuring error, a convector for controlling the overturning measurement was filled in (Fig. 1, Allen, 1971).

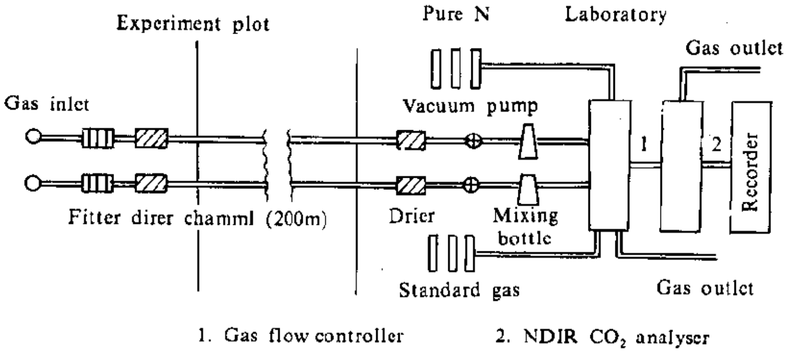

Fig. 1 Air channel system for the measurement of CO_2 concentration and its difference

Such design had avoided different errors. Because it allowed two air streams get into two chambers periodically and alternatively, was fitted in the convector for controlling the channel overturning, the errors of zero shift of the analyzer and the systematic errors of air channels can be eliminated automatically. Thurlby-1905 Voltmeter with 6-digit was used for recording to improve the precision and the resolution of measurement. The air sample was transferred through the channel with a length of 200 m, filtered, dried and mixed in a bottle, then got into the analyzer.

In 1981, the sampling plots were set up at Crop Breeding Center (CBC) of Luancheng County, 20 km south of Shijiazhuang, Hebei Province. There are a lot of wheat field around the plots. Experiments included plots with rich and moderate fertility. The observation plots were set in the field of rich production. Variety of wheat was Taishan-5. After 1984, observation was carried out in Datun Experimental Station of Agroecological System (ESAS) in Beijing. The wheat varieties were Fengkang-2 and Jinghua-3 with average yield of 4500 kg/ha. And that of maize was Yedan-4 with average yield of 7500 kg/ha. Growth and development in different stages were measured and dry matter was weighed.

Observation items of field microclimate included global radiation, net radiation, heat flux of soil and gradient observation of temperature, humidity and wind. Systematic observation of field microclimate was carried out in different growth stages, 8−9 times in whole growing season and 2−3 days each time. The interval of measurement was 1−2 h .

2 Analysis and results

2.1 Variation of CO_2 concentration near crop canopy

According to the data CO_2 concentration during growing seasons of wheat and maize in several years, the trends of variation of CO_2 concentration near crop canopy during the season were almost the same in spite of obvious variation of the atmosphere background. CO_2 concentration was continuously decreasing in the daytime, and increased in the night, and reached its maximum before sunrise. The daily amplitude was quite big. Typical data obtained on fine days in the field of rich production (yield about 6000 kg/ha) in CBC of Luancheng are shown in Fig. 2. When photosynthesis was strong in the day, CO_2 concentration is 250−300 ppm, which was similar to the data of Holibu (Holibu, 1964) obtained in paddy field at a height of 100 cm and is coincide with results of Uchijima (Uchijima, 1967) and Allen (Allen, 1971).

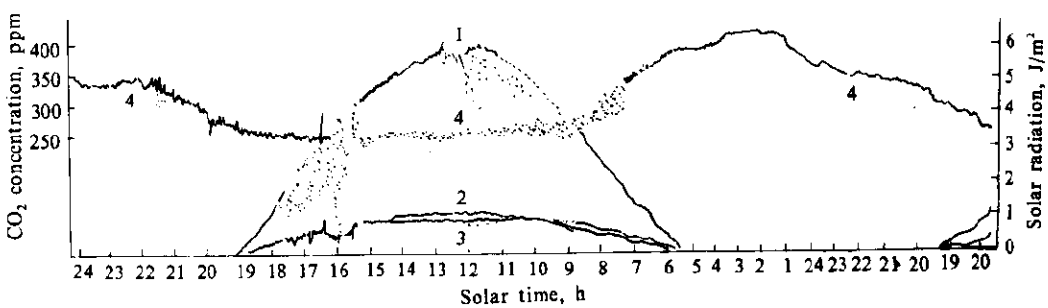

Fig. 2 Diurnal variation of CO_2 concentration in the air above wheat field (May 12, 1981)

1. Irridiance; 2, 3. the reflected solar radiation of bare soil and wheat field, respectively; 4. CO_2 concentration

Due to the effects of turbulent transfer, CO_2 concentration in the field was fluctuating continuously and the fluctuating amplitude was several ppm in most cases (Fig. 3). Our observation results were consistant with Lemon's (Lemon, 1964) report of ±10ppm variation at 1 m above the ground. It became difficult to calculate the small instantaneous difference of CO_2 concentration between different heights near the canopy. Therefore, the sample to be measured had to be fully mixed in a bottle to obtain the average value.

Daily curves of CO_2 concentration at 2m above the canopy of winter wheat or summer maize are shown in Fig. 4 in which the data were obtained on several typical dates with fine weather and breeze wind during the vigorous growing season As this experiment was carried out in ESAS near the city of Beijing, the background CO_2 concentration was high.

There was obvious diurnal variation of difference of CO_2 concentration at two heights near the canopy. Fig. 5 shows the difference between 1.6 and 1.0 m above the ground of wheat field. It is stable in the day when wheat photosynthesis was vigorous in the filling slage, the flux was from the canopy to the atmosphere. But the direction in the night was opposite. Because of weak turbulent exchange and strong respiration of crop from 0−6 a.m., in the night the flux was towards the atmosphere. The difference of CO_2 concentration between two layers of air stream with interval less than 1 m was big and was able to reach 30−40 ppm sleadily. Therefore, CO_2 flux density could be calculated from the difference of CO_2 concentration, temperature and wind speed of different heights above the canopy.

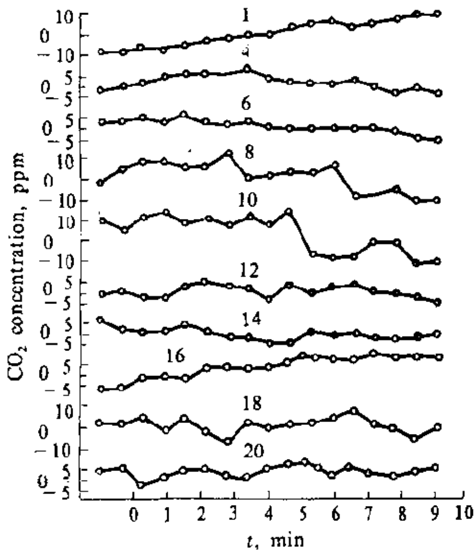

Fig. 3 Fluctuation of CO_2 concentration in wheat field (1981)

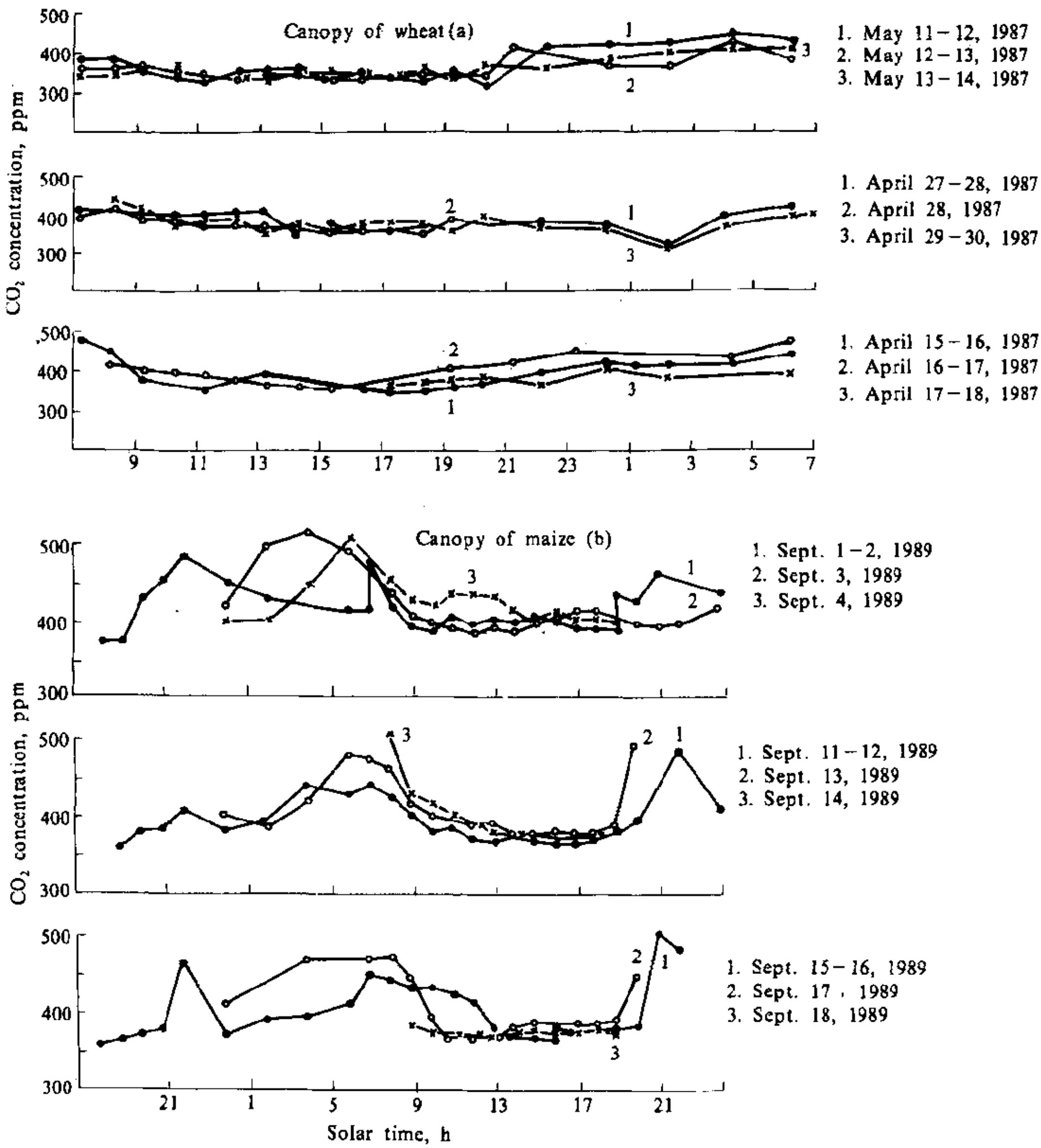

Fig. 4 Diurnal variation of CO_2 concentration at 2 m above the canopies of winter wheat (a) and summer maize (b)

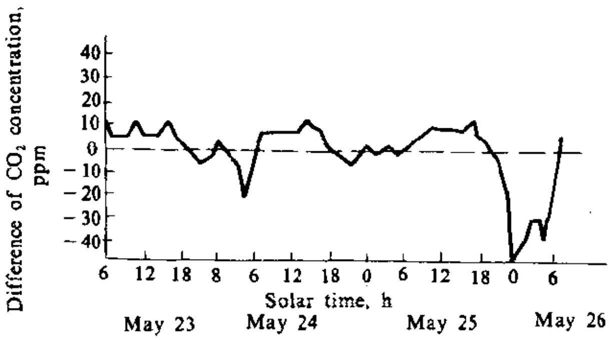

Fig. 5 Diurnal course of the difference of CO_2 concentration above the canopy of wheat (May 23—26, 1989, in filling stage, H=1.6m and 1.0m)

2 The variation of CO_2 flux density in wheat and maize fields

Field CO_2 flux density can be calculated by aerodynamic method with data of temperature, wind velocity and so on.

In neutral condition logarithmic profile of wind velocity can be expressed as the following equation for uniform rough surface of plants:

$$\frac{\bar{u}}{u_*} = \frac{1}{k} \ln \left(\frac{z-d}{z_0} \right), \tag{1}$$

where $\bar{u}$ is the average velocity, u_* is the friction velocity, k is Karman constant, d is the zero-plane displacement, z_0 is the height of rough surface, z is the height above ground, d and z_0 are both independent arbitrary constants. Equation (1) is meaningful only when $z \geqslant d + z_0$, d can be worked out from wind velocities, of three heights. Various parameters were determined by author using Equation (1) and empirical method. It shows that d and z_0 were related with the height of plant H. Monteith (Monteith, 1973) proposed the following linear relation, i. e. $d = 0.63\ H$, z is often assumed as 1/10 of H. When d and z_0 were known, the whole profile above the canopy can be derived u at one height. Values at other height can be worked out by:

$$\bar{u}\ (z) = \frac{u_*}{k} \ln \left(\frac{z-d}{z_0} \right), \tag{2}$$

$$u_* = \frac{k\bar{u}\ (z)}{\ln \left(\frac{z-d}{z_0} \right)} = C_M \bar{u}\ (z)\ , \tag{3}$$

where C_M is usually called drag coefficient.

The general equation to calculate CO_2 flux density F_C can be expressed as

$$F_c = fK^2 (z-d)^2 \frac{\partial u}{\partial z} \cdot \frac{\partial c}{\partial z} (\varphi_m)^{-2} \frac{K_c}{K_m} , \tag{4}$$

where $\frac{\partial c}{\partial z}$ is gradient of CO_2 concentration, f is the coefficient of transformation from volume concentration (ppm) to weight per unit volume at different temperature, φ_m is the universal function of stability, K_c/K_m is the ratio of CO_2 exchange coefficient K_c to momentum exchange coefficient K_m, both are function of Ri (Richardsen number) and L (Monin-Obukhov length).

$$\frac{\partial u}{\partial z} = \frac{u_* \varphi_m}{Kz} = \frac{C_M \overline{u}(z)}{Kz} \cdot \varphi_m , \tag{5}$$

where φ_m is stability function of momentum which is different from φ_v, φ_H, φ_c, i. e. stability function of water vapor, heat and CO_2 . But there are still argument whether their values are equal.

Based on Monin-Obukhov theory, φ can be determined by

$$\varphi = (1 - a \frac{z-d}{L})^{-n} . \tag{6}$$

Many authors pointed out that $\frac{z-d}{L}$ and Ri were equivalent. Some authors deduced many forms of φ. Dyer and Hicks (Dyer, 1970) concluded that there was almost no difference between φ_V and φ_H even under an unstable condition.

Based on the model of Pruitt (Pruitt, 1973), under unstable stratification, $\varphi_m = (1 - 16Ri)^{-\frac{1}{3}}$, $K_W/K_m = 1.13\ (1 - 60Ri)^{0.074}$, and under stable stratification, $\varphi_m = (1 + 16Ri)^{\frac{1}{3}}$, $K_w/K_m = 1.13\ (1 + 95\ Ri)^{-0.11}$. Assuming $K_w = K_c$, flux density of wheat canopy was calculated by using equations mentioned above.

Because of decrease of the fetch, K_c in maize field (1989) was determined by energy balance method and then CO_2 flux can be worked out.

Data collected in plots of CBC in Luancheng are listed in Table 1. The flux from the air above canopy to the canopy was positive and it was negative on the contrary. In early growth stages, e. g. April, CO_2 flux in the day was always from the atmosphere to the canopy. It gradually decreased obviously after May. The flux was even from the canopy to the atmosphere at sunrise and before nightfall. CO_2 concentration increased rapidly near the canopy in June. On 3 – 4 June wheat was fully mature, the flux direction was from the canopy to atmosphere almost whole day to the respiration of seeds and withered stems and leaves. Wheat was harvested late in Luancheng County. Therefore loss due to the respiration was big and the yield would be affected. Because air temperature of wheat maturing season in North China

Plain was often high. Wheat harvest needed to be carried out in time.

Diurnal observation data of wheat in ESAS, data in 1985 are shown in Fig. 6. The flux in the day was from the atmosphere to the canopy. Big flux density occurred from 9 a. m. to 16 p. m. and the maximum at about 11 a. m. Conversely, it was negative in the night, i. e. from the canopy to the atmosphere. This was

Table 1 CO_2 flux density in wheat field in different developmental stages

Date	Developmental stages	CO_2 flux density during days, 10^{-6}kg/(m^2.s) 7	9	11	13	15	17	19	Total solar radiation, J/(cm^2.s)	Wind speed at 2m height, m/s	Mean air temperature of 7−19h, ℃
Apr. 10	Elongation	0.66	3.69	0.30	0.44	0.12	0.18	2.33	1409.3	1.5	18.5
Apr. 11	Elongation	0.00 *	4.35	2.11	2.21	4.56	1.36	0.36	2212.3	1.7	18.6
Apr. 24	Earing	2.15	1.06	4.26	2.33	5.10	1.42	0.04	2672.4	1.8	18.5
May 12	Graintilling	0.22	0.76	0.88	2.87	1.04	1.66	0.48	2912.8	1.2	20.5
May 13	Graintilling	0.14	0.01	0.08	1.47	2.90	3.10	0.00	2290.7	2.0	22.1
May 14	Graintilling	−0.41	0.79	0.77	0.90	0.76	1.39	0.69	2866.8	1.6	22.3
June 3	Maturing	0.00	−4.65	0.00	−3.92	−1.94	−0.63	−0.81	2962.9	2.0	29.0
June 4	Maturing	−2.54	−0.97	2.87	−3.13	−1.12	−3.23	−1.14	2950.4	1.0	28.1

Source: At plot in Luancheng, 1981

coincide with the results of Rosenbarg (Rosenbarg, 1976) and Denmead (Denmead, 1966). Because developmental stages of winter wheat in Beijing are about 7−10 days later than that in Luancheng, the flux was still from atmosphere to the canopy in the beginning of June and there was still strong photosynthesis in the day.

There were similar patterns of CO_2 flux of maize field. Fig. 7 shows CO_2 flux in filling stage of maize which reaches maximum at noon and turns negative in the night. Photosynthesis was not vigorous due to entering the late stage development.

There was close relation between CO_2 concentration and the flux of global solar radiation near canopy. Fig. 8 shows that CO_2 flux density increased with the increase

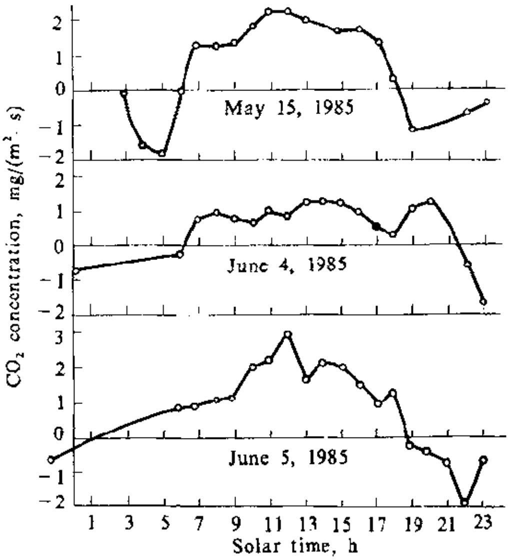

Fig. 6 CO_2 flux density (80−200cm) under condition of typical fine weather in wheat field (Beijing, 1985)

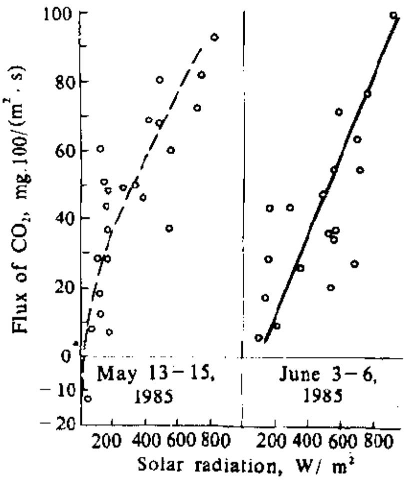

Fig. 7 CO_2 flux variation under condition of typical fine days in filling stage of maize (Beijing, September 13, 1989)

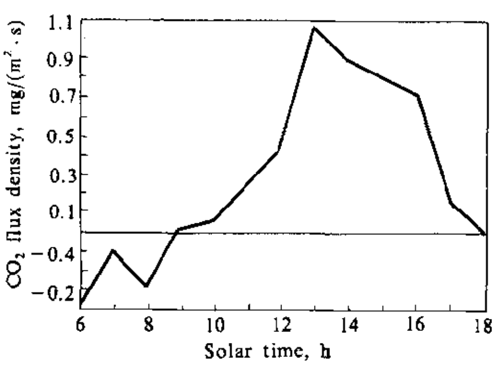

Fig. 8 Relation between CO_2 flux density and global radiation in wheat field (Beijing, 1985)
a. May 13−15; b. June 3−6, 1985

of flux of global solar radiation. The effect of wind speed was not significant. This trend in heading stage (May 13−15) and was the same as in filling stage (June 3−4).

In 1988, relations of CO_2 flux (Fc) to net radiation (Rn), CO_2 exchange coefficient (Kc) and wind velocity (u) in wheat field were studied (Fig. 9). Fc is related with Kc and increase as Kc increases, but was not significantly related with Rn and u.

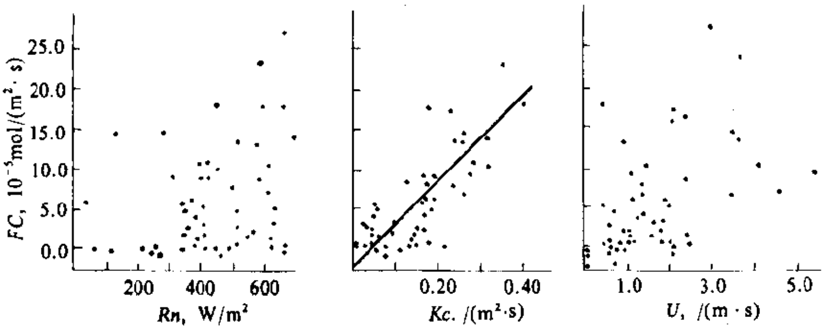

Fig. 9 Relation of CO_2 flux (Fc) to net radiation (Rn), CO_2 exchange coefficient (Kc) and wind speed (u) in wheat field

3 Conclusions

CO_2 concentration in field was measured by an infrared CO_2 analyzer, and field microclimate parameters were observed synchronously. CO_2 flux density was calculated by aerodynamic method. Fairly satisfying results were able to obtain and with other researchers. This method can be used to determine mass and energy flow in the field, to study primary crop productivity qualitatively, and to determine CO_2 flux density in the boundary of ground and atmosphere, and the exchange and transfer of other trace gases, too.

Based on several years data, CO_2 concentration of 250–300 ppm was often observed in early 1980s, when deficiency of CO_2 was paid close attention to and was considered as a limited factor of productivity. But the results in recent years showed that CO_2 concentration in the field was always more than 300 ppm and even high. This may be related with increase of background value of CO_2 in the atmosphere. The effects of CO_2 increase on plants and crop productivity were becoming an attentive problem day by day.

Analysis showed that relations of field CO_2 flux to global solar radiation and CO_2 exchange coefficient were more significant than that to net radiation and wind speed. Further studies on relations of CO_2 flux to meteorological factors and crops will be helpful to determine CO_2 flux density in large area, and will be significant for research micrometeorology, field ecology and vegetation productivity.

References

Allen LHJr. Agr Meteorol, 1971; 8:5

Denmead OT. Proceeding of the world meterological organization seminar on agricultural meteorology. 1966:445

Goudriaan J. Crop meteorology: A simulation study, Center for Agricultural Publishing and Documentation, Workshop on micrometeorology, Huagen D. A: The American Meteorological Society, 1963

Holibu S, Agrometeorology, 1964; 19(4)

Liu Xuan, Yu Huning. Plant Physiology Communications, 1989; (2):64

Lemon E, Wright JL, Drake GM. Agron J, 1969; (61):411

Monteith JL. Principles of environmental physics. London: Edward Arnold, 1973

Monteith JL. Vegetation and the atmosphere (Vol. 1) . London: Academic Press, 1975

Pruitt WO, Morgan DL, Lourence FJ. GJR Meteorol Soc, 1973; 99:370

Pearman GI, Atmospheric CO_2 concentration measurements: a review of methodologies, existing programmes and available data, WMO report (3), 1980:3

Rosenberg NJ, Verma SB. Agronomy Journal, 1976; 68:414

Uchijima Z, Udagawa T, Horie. Kobayashi. Agr Meteorol, 1968; 3:99

Yu Huning, Lu Xuan. A study on the CO_2 flow in a crop field. Proceeding of international symposium on agricultural meteorology, Beijing: China Meteorological Press, 1987

(Received July 14, 1992)