A MEASURING SYSTEM OF TURBULENT TRANSPORT AND ITS FIELD TEST OVER A BARLEY FIELD*

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INTRODUCTION

The necessity of measuring the vertical turbulent transports of momentum, heat, water vapor and carbon dioxide over the plant canopy has been recognized for a long time. A number of measurements have been made by the use of the aerodynamic method or heat balance method, and results adequate for specific purposes have been obtained by these methods. In recent years, a more direct method of determining turbulent fluxes has been made practicable by the development of the sonic anemometer or propeller anemometer as stable, fast response wind sensors (Japan-U.S. Joint Study Group 1971; Dyer 1967). A difficulty in the application of this eddy correlation method is the enormous amount of data to be analyzed in the measurements over a longer period. Two models of eddy correlation instruments devised in our country, Assimitron (Inoue et al. 1969) and HYSAT (Hanafusa 1971) are equipped with relatively complex systems to process the data. In this paper, a simplified method of measuring turbulent transports, which has been designed on the basis of the results of these studies, is described and results of test experiments over a barley field are presented.

MEASURING SYSTEM OF TURBULENT TRANSPORT

In the present system Reynolds stress $\tau = -\rho\overline{w'u'}$ is measured by the eddy correlation method, where ρ is the air density, u' and w' fluctuations of the horizontal and vertical components of wind and the bar represents a time average. An eddy transport coefficient $D_m = -\overline{w'u'}/\Delta\bar{u}$ is estimated from the covariance $\overline{w'u'}$ and the wind speed difference $\Delta\bar{u}$ measured at two heights. The differences of air temperature, specific humidity or CO_2 content measured over the same height interval, multiplied by D_m, give fluxes of heat, water vapor or CO_2.

Fig. 1 shows the block diagram of the main part of this system which consists of sonic anemometers (Mitsuta 1966) and an analog data analyzer (Kaijodenki, Model AD-801).

A sonic anemometer with a vertical sensing path of 20 cm (Kaijodenki, Model PA 112-1) measures the vertical component of wind velocity w. A

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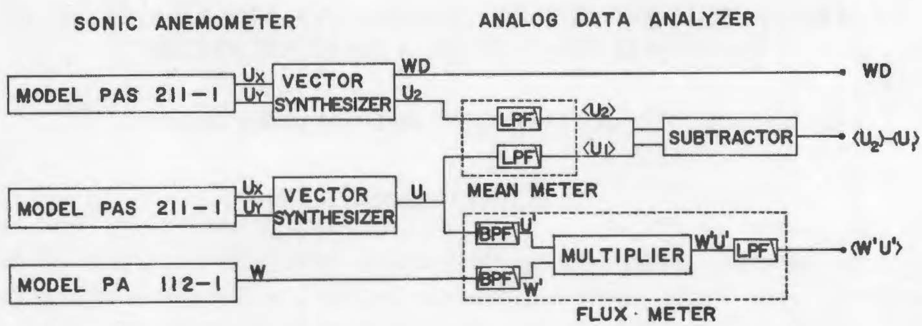

Fig. 1. Block diagram illustrating the method of measurement of turbulent flux and transport coefficient for momentum.

two dimensional sonic anemometer (Model PAS 211-1) measures the wind components along two horizontal sensing paths of 20 cm crossed at 90°; from these wind components the horizontal wind speed u and wind direction WD are obtained with a vector synthesizer unit (Mitsuta 1971). The wind speed range can be selected out of three ranges ± 1, ± 3 or ± 10 m/s, with an output ± 1 V.

The flux meter unit of the data analyzer is used to evaluate the covariance $\overline{w'u'}$. The two signals u and w passed through a band pass active filter with cutoff frequencies: 0.01-10 cps yield signals representing fluctuations u' and w' with a sampling time of 44 sec and an averaging time of 0.044 sec. The cutoff frequency given above is the frequency at which the response is 3 dB below the passband gain. The products of signals u' and w' are computed by an analog multiplier. The time average of the products $\langle w'u' \rangle$ is obtained with the low pass active filter of cutoff frequency 0.005 cps with a corresponding averaging time of 88 sec. The frequency response of the flux meter unit is seen from the calibration curves in Fig. 2. The solid line of the figure shows the covariance re-

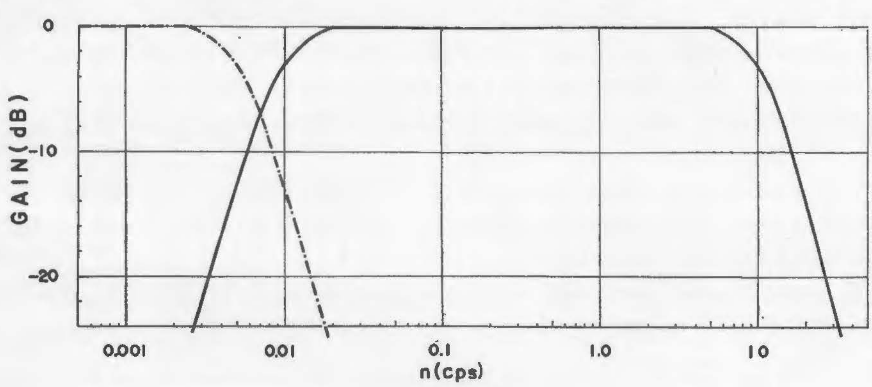

Fig. 2. Filter response curves of flux meter unit. Solid line: band pass filter. Dot-dash line: low pass filter.

sponse of the flux meter. The dot-dash line shows the filter characteristics of the low pass filter at the final stage of the circuitry for averaging the signals $w'u'$. The flux meter is calibrated by giving in-phase sinusoidal input ± 1 V of 0.1 cps on each channel so that the multiplier yields the output of 1 V in peak value and the low pass filter the averaged output of 0.5 V. The amplifier settings in the flux meter are adjustable, depending on the magnitude of the fluctuations.

The wind speeds u_1 and u_2 at two heights z_1 and z_2 $(z_1 < z_2)$ are measured with the sonic anemometers of Model PAS 211-1, one of which is the same unit as used in the measurement of $\langle w'u' \rangle$. The signals of horizontal winds are fed to the mean meters to yield $\langle u_1 \rangle$ and $\langle u_2 \rangle$, and the difference $\langle \Delta u \rangle = \langle u_2 \rangle - \langle u_1 \rangle$ is taken by the subtractor unit. The mean meter is a RC active filter of cutoff frequency $f_c = 0.01$ cps. The output obtained by this mean meter is equivalent to a mean value over the sampling time of 44 sec. From the records of $\langle w'u' \rangle$ and $\langle \Delta u \rangle$, average values $\overline{w'u'}$ and $\overline{\Delta u}$ for a longer sampling duration, say 15 min, are constructed, and the transport coefficient $D_m = -\overline{w'u'}/\overline{\Delta u}$ is evaluated.

The heat flux H, water vapor flux E and CO_2 flux F_{CO_2} can be estimated from the following relations under the assumption of similarity between the diffusivity for momentum and that for heat, water vapor or CO_2:

$$H = -c_p \rho D_m \Delta \overline{T},$$
$$E = -\rho D_m \Delta \overline{q},$$
$$F_{CO_2} = -D_m \Delta \overline{C},$$

where ΔT, $\Delta \overline{q}$ and ΔC are the difference of air temperature, specific humidity and volume concentration of CO_2 measured over the same height interval as for Δu, c_p the specific heat at constant pressure of the air. The data on $\Delta \overline{T}$, $\Delta \overline{q}$ and $\Delta \overline{C}$ can be obtained by various methods and the methods adopted in the present study are indicated in the following section.

FIELD EXPERIMENT

The test experiment was carried out on a barley field of the experimental farm of Faculty of Agriculture, Okayama University, during 12-18 May 1971. The experimental farm is located at Hachihama on a reclaimed land from Kojima Bay. The topographic map of the site is shown in Fig. 3; the position of the observed point is marked by a circle. The figure shows the general flatness of the reclaimed land. The barley field surrounded by stubble fields had the area of 120×120 m. The nearest obstacles were barns and a garage to the south at a distance of about 60 m from the instrumental poles. The barley was 100 cm high and in the ripening stage.

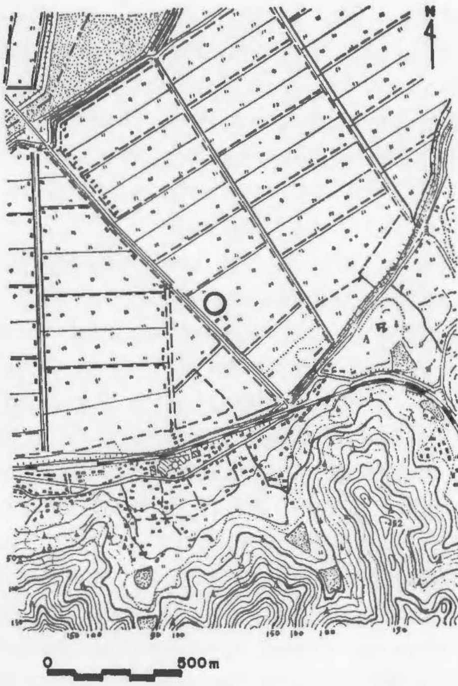

Fig. 3. Map of the Hachihama site, showing position of experimental area.

The probe of Model PA 112-1 as a vertical wind sensor was mounted on a horizontal boom supported by a tripod at a height 1.4 m above the ground. Horizontal wind sensors of Model PAS 211-1 were mounted on separate poles at two heights of 1.4 m and 3 m. The vertical and horizontal wind sensors at the lower height were arranged so that the centers of the sensing paths were nearly coincident.

Recorders and monitoring instruments were located in a garage 60 m apart from the measuring point. The output for $\langle w'u' \rangle$ was typically a few tens of millivolt and that for $\langle \Delta u \rangle$ a few hundreds of millivolt. These outputs $\langle w'u' \rangle$ and $\langle \Delta u \rangle$ were recorded with the appropriate attenuations on a self-balancing potentiometric recorder of the range -2 to 8 mV. The covariance $\langle w'u' \rangle$ and wind speed difference $\langle \Delta u \rangle$ were read every minute and averaged over 15 minutes. The drift of electronic zero of the system, which was checked at intervals of several hours during the field experiment, was not negligible and readings of the records were corrected for the zero drift. The transport coefficient $D_m = -\overline{w'u'}/\Delta\bar{u}$ was calculated from the momentum flux at 1.4 m and wind speeds at 3.0 and 1.4 m height.

Besides the above mentioned mean values, the winds from the sonic anemometers and the instantaneous product of fluctuations u' and w' were occasionally recorded on a pen oscillograph (Watanabe Sokki, WTR-281) in order to monitor the performance of the measuring system.

In support of the measurements with the sonic anemometers the following observations were taken: a) vertical difference of dry- and wet-bulb temperature between two levels (1.4 and 3 m) with aspirated shielded thermocouple thermometers; b) difference of atmospheric CO_2 content between 1.4 and 3 m with an infrared gas analyzer URAS (for the measurement with URAS, see Ohtaki and Seo 1972); and c) net radiation with a Funk net radiometer mounted at the height 1.4 m, and soil heat flux with a heat flux plate (Eiko Seiki). The data were reduced to give 15 min average values.

The field experiment was carried out during the period from 12 to 18 May. General observations were taken in two periods 12 to 13 May and 17 to 18 May. Winds were generally southeasterly on 12 and 13 May and westerly on 17 and 18 May. During the period of the experiment, the weather was generally fair with clear to broken sky except showery weather on 14 to 15 May.

RESULTS AND DISCUSSIONS

Samples of three recorded fluctuating signals of w, u and $w'u'$ observed at the height of 1.4 m are given in Fig. 4. The w- and u- traces show that the vertical velocity component w contains high frequency fluctuation compared with the horizontal component u. It is seen that the product $w'u'$ has negative values for the most of the time showing large values intermittently. This burst-like phenomenon, which indicates an abrupt

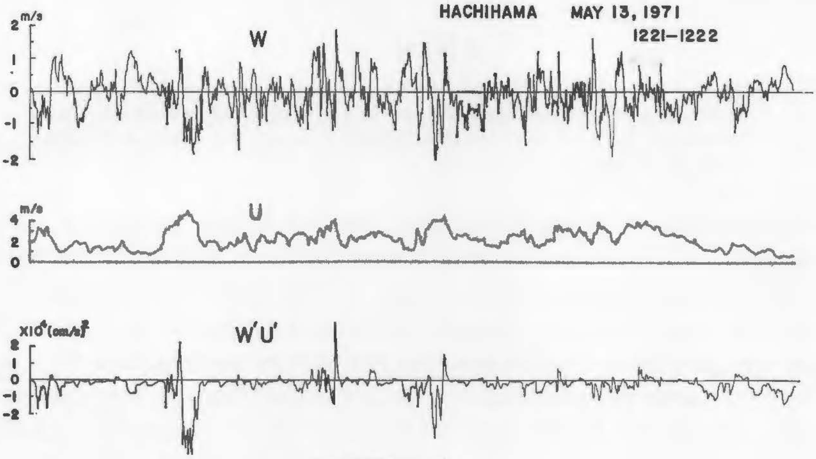

Fig. 4. An example of oscillograph traces of vertical wind w, horizontal wind u and product of fluctuations w' and u'.

momentum transport of short duration in air flow with large shear as noted by Mitsuta (1968), should be considered in determining the sampling duration. The period of intermittency is of the order of tens of second, suggesting that the sampling duration of 15 min is sufficient in the measurement at 1.4 m height.

To investigate whether the band pass filter used in the flux meter is adequate for the flux measurement, the cospectra between w and u have been obtained with Tukey's method for two cases of moderate and light winds. The computation has been carried out on a KDC-2 and a Facom 230-60 computer at the Data Processing Center of Kyoto University. The results are represented in Fig. 5 and 6. In the figures, normalized power

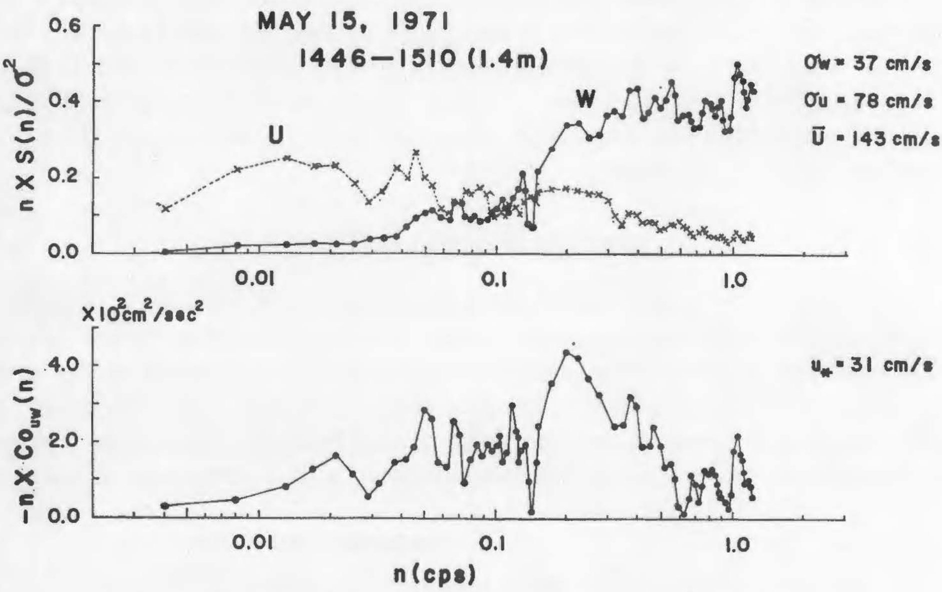

Fig. 5. Normalized spectra of wind velocity components u and w and cospectrum between u and w in a case of moderate wind speed of 1.4 m/s. u_*: friction velocity, σ_w and σ_u: standard deviation of w and u.

spectral densities of vertical velocity w and horizontal velocity u are plotted for reference. In the case of wind speed of 1.4 m/s (Fig. 5) the horizontal wind velocity has considerable energy at the lower frequencies, whereas the vertical wind velocity contains little energy below 0.01 cps. The frequency range which contributes mainly to the momentum flux is from 0.01 to 1 cps and the contribution is not significant at frequencies below 0.01 cps. However, in the case of light wind of about 30 cm/s (Fig. 6), where the contributions to the power of wind speed come from lower frequencies than in the case of moderate wind, non-negligible portion of momentum flux (30% of total) is contained in the frequency range lower

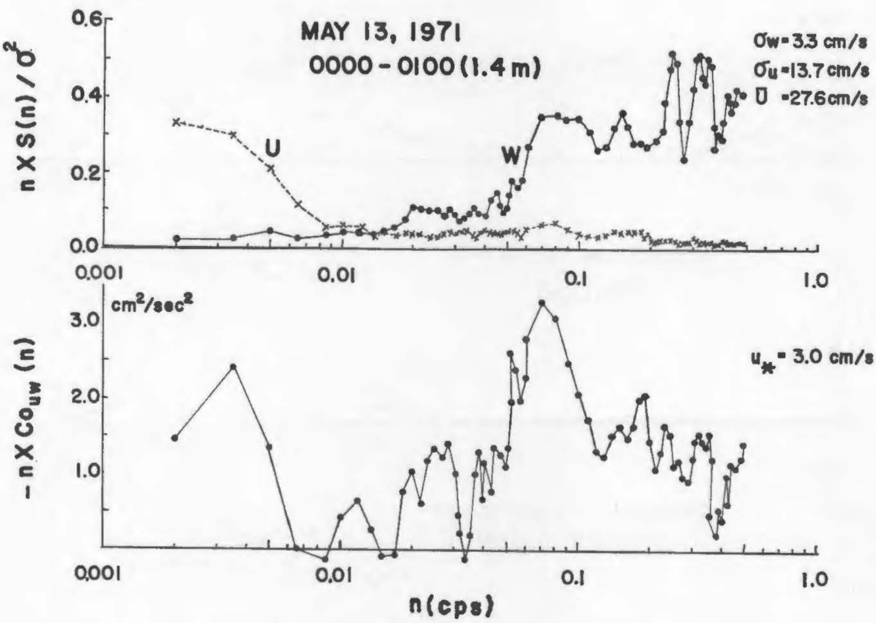

Fig. 6. Normalized spectra of wind velocity components u and w and cospectrum between u and w in the case of low wind speed of 0.3 m/s.

than 0.01 cps. For the frequency $n=0.01$ cps with $\bar{u}=30$ cm/sec and $z\text{-}d=80$ cm, the normalized frequency defined as $f=n(z\text{-}d)/\bar{u}$ is approximately equal to 0.03. Here the zero plane displacement d is taken as 60 cm, a value as estimated in the next section. The results summarized by Panofsky and Mares (1968) also show that a considerable portion of momentum flux is contained in the frequency range below this value of normalized frequency. It is expected that the cutoff frequency of 0.01 cps on the lower frequency side adopted in the band pass filter involves an underestimate of the momentum flux and eddy transport coefficient in light wind conditions.

Diurnal variations of momentum flux and transport coefficient are shown in Fig. 7 for the period from 12 to 13 May. The wind speed is also represented in the figure. The wind speed at 1.4 m showed a typical diurnal variation in the surface layer: the wind speed was low through the night and morning and began to increase before noon to attain a maximum of about 3 m/s at about 15 hr. Corresponding to this diurnal variation of wind speed, the covariance $-\overline{w'u'}$ of momentum flux varied from values of the order of 10 cm^2/s^2 in the nighttime to a maximum of 3×10^3 cm^2/s^2 in the daytime. The latter value of momentum flux is equivalent to the drag force of 3.6 dynes/cm^2. The diurnal variation of transport coefficient closely followed the variation of wind speed and its

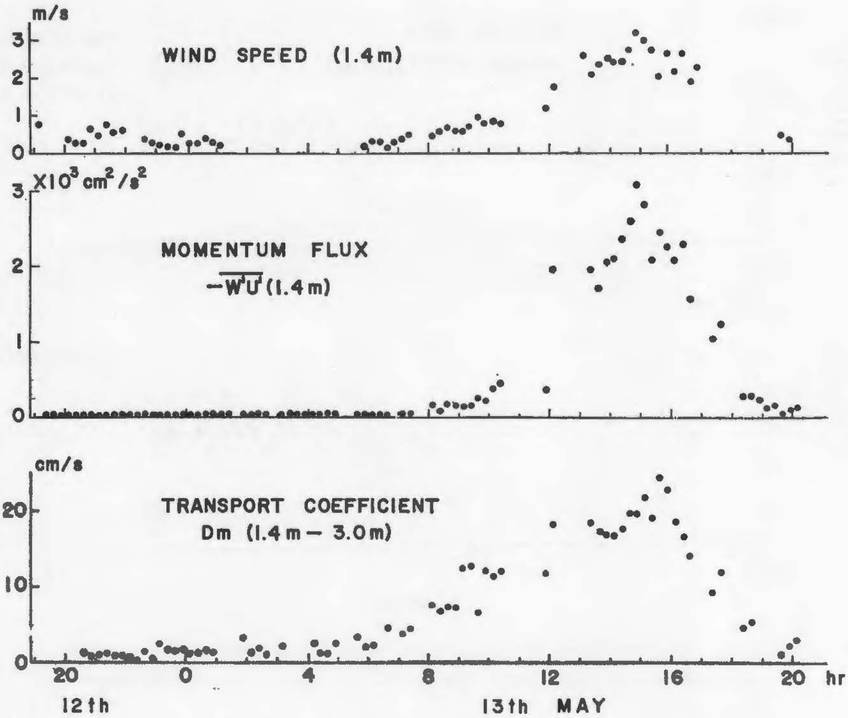

Fig. 7. Diurnal variation of wind, momentum flux and transport coefficient over barley on 12 to 13 May, 1971.

values ranged from the order of 1 cm/s in the nighttime to 20-30 cm/s around 15 hr on 13 May. It is estimated that the transport coefficient can be determined by the present system up to two significant figures in moderate wind conditions and to one significant figure in light wind conditions. It is noted that the transport coefficient showed higher values in the morning hours than in the night for approximately equal wind speeds. This is probably due to the difference in the stability condition.

The CO_2 flux, calculated from the transport coefficient as determined above and the CO_2 difference measured between 3.0 m and 1.4 m, is shown in Fig. 8 for the period 12 to 13 May. The net radiation and the CO_2 difference are also shown in the figure. The CO_2 difference showed large variabilities in the nighttime ranging from −10 ppm to −60 ppm and was relatively steady in the daytime with values of 2 - 3 ppm. The CO_2 flux was directed downward during daylight hours and upward during the night; the transition in the morning occurred about one hour later than the time of sunrise. The CO_2 flux in the daytime, except for early morning and late afternoon, varied between 0.1 and 0.2 mg/cm^2 hr with no distinct maximum. The upward flux during the night was relatively steady until midnight and showed appreciable scatter from the midnight

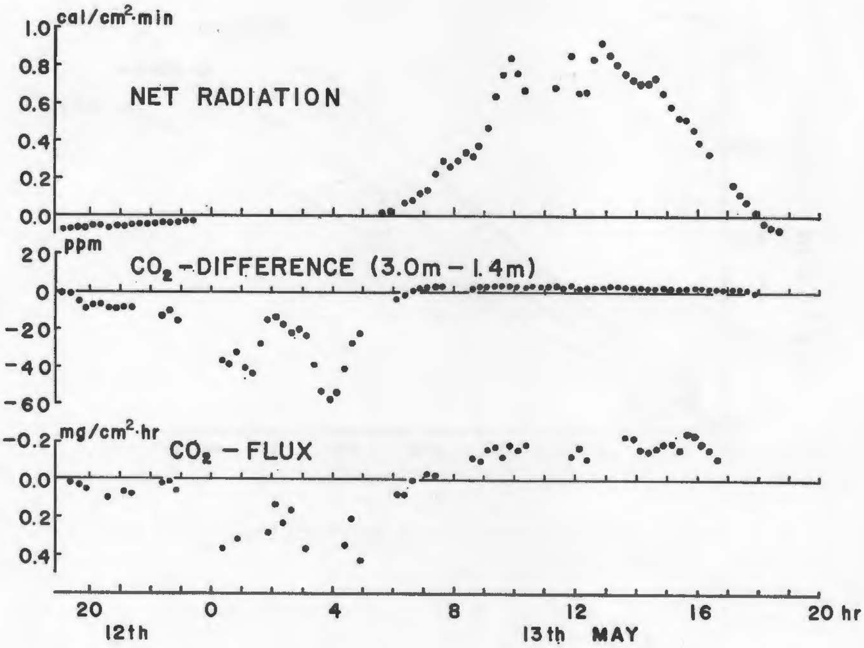

Fig. 8. Diurnal variation of CO_2 difference and CO_2 flux together with variation of net radiation on barley field on 12 to 13 May, 1971.

to the morning. The large variability of CO_2 flux during the night has been observed over a paddy field in calm conditions (Ohtaki and Seo 1972). The total daytime downward flux of CO_2 in this period was estimated to be about 1.6 mg/cm^2 and the nocturnal upward flux about 2.2 mg/cm^2. The net uptake of atmospheric CO_2 by the crop stand was -0.6 mg/cm^2 day. This negative value is acceptable considering the reduction in the assimilation rate of the crop in the ripening stage.

The reliability of the measurement of covariance $\overline{w'u'}$ and wind speed difference $\Delta\bar{u}$ is examined below.

1) Fig. 9 shows the relation of wind difference $\Delta\bar{u}$ to friction velocity $u_* = \sqrt{-\overline{w'u'}}$, from the data on 12-13 and 17-18 May. Lines entered in the figure represent the theoretical relation $\frac{\Delta\bar{u}}{u_*} = \frac{1}{k} \ln\frac{z_2-d}{z_1-d}$ with three different values of zero plane displacement d. The measurements give an approximate value $d=60$ cm for the barley stand, which is within a reasonable range for the crop height of 100 cm (Stanhill 1967).

2) The drag coefficient $C_D = -\overline{w'u'}/\bar{u}^2$ referred to wind speed at 3 m height varied in the range from 5×10^{-3} to 5×10^{-2} with a mean of 2.0×10^{-2}. This mean value is of comparable order with the values observed by Inoue et al. (1951) over the paddy rice 80 cm high. The drag coefficient is shown as a function of wind speed in Fig. 10 for wind speeds above

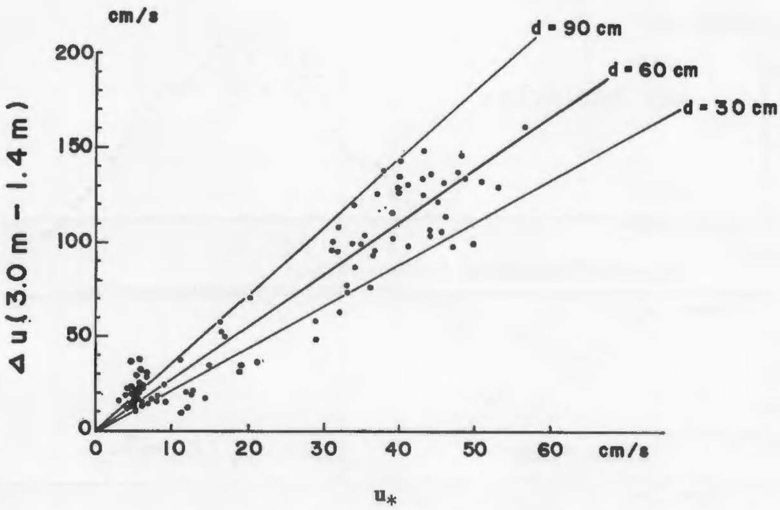

Fig. 9. Relation between wind speed difference $\Delta\bar{u}$ and friction velocity u_*.

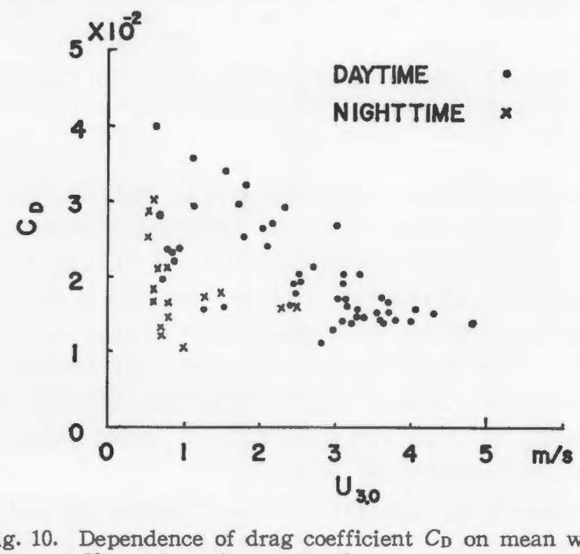

Fig. 10. Dependence of drag coefficient C_D on mean wind speed $U_{3.0}$ at 3 m above ground.

50 cm/s. A large variability is evident in the figure, particularly at low wind speeds. The values in the nighttime tended to be smaller than those in the daytime. It is also seen in this figure that the drag coefficient for the daytime increases with decreasing wind speed. Fujitani et al. (1970) observed a similar tendency over a bare ground. It is supposed that this is partly due to the effect of stability on winds in the surface layer and partly due to the changes in the surface roughness consisting of easily movable plants.

3) Data adequate for heat budget considerations are available for periods from 12 hr on 17 May to the midnight of the following night and 10-12 hr on 18 May. The time variations of heat balance components are illustrated in Fig. 11. Fluxes of sensible and latent heat estimated by

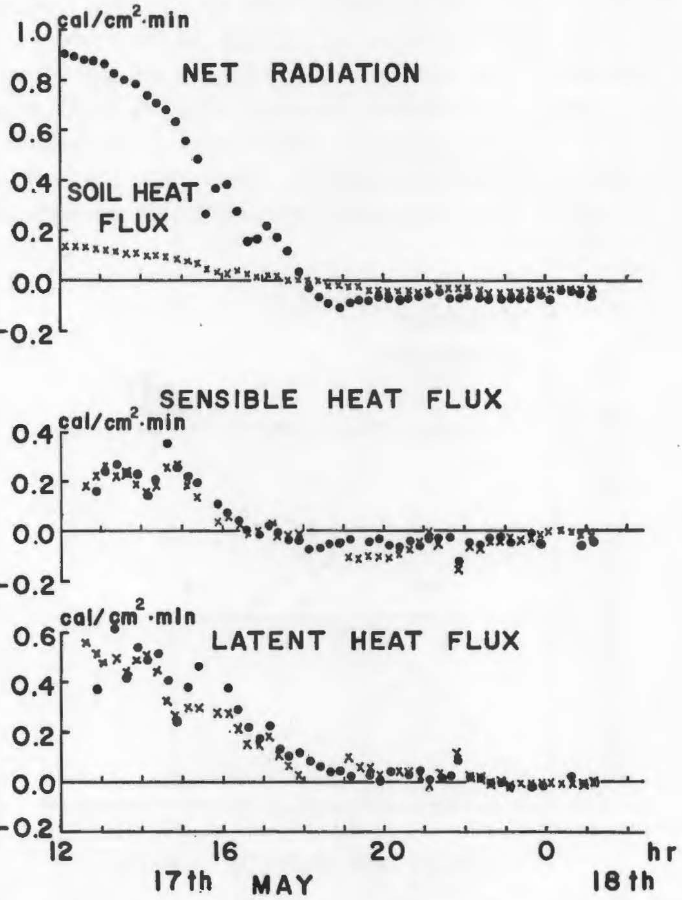

Fig. 11. Time variation of heat balance components for the period from 12 hr on 17 May to the midnight of the following night. In the figures for sensible and latent flux, • represents values by present method and × values by heat balance method.

the present method (•) and by the heat balance method (×) are compared in the lower two figures of Fig. 11. The time variations of the fluxes by both methods are seen to be in fair agreement. It is remarked that around sunset and during midnight hours the heat balance method could not provide reliable estimates of fluxes because of net radiation nearly balanced by soil heat flux or small values of temperature gradient.

A more relevant test of the method is provided by the comparison of the transport coefficient obtained by the present method D_m $(=-\overline{w'u'}/\overline{\Delta u})$

with that by the heat balance method D_H ($=\frac{\bar{S}-\bar{B}}{\rho(C_p+L\frac{\partial q}{\partial T})\Delta T_W}$), where S is the net radiation, B the soil heat flux, ΔT_W the wet-bulb temperature difference and $\partial q_S/\partial T$ the rate of change with temperature of saturation specific humidity. The comparison is made by the data from the observation 17-18 May in Fig. 12; data on 12 and 13 May were not available due to malfunction of the wet-bulb temperature sensor. Daytime values of momentum transport coefficient appear slightly high compared with those from heat balance method. Nighttime values show appreciable scatter. In spite of these uncertainties, the correlation is fairly high and it may be concluded that the present method yields a reasonable estimate of transport coefficient.

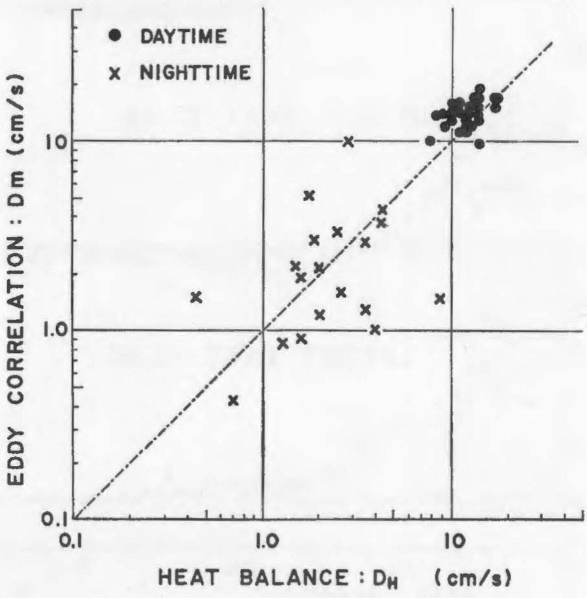

Fig. 12. Comparison between transport coefficient by eddy correlation method D_m and that by heat balance method D_H. $D_m=D_H$ line is entered for reference.

CONCLUSIONS

A simplified measuring system designed to measure the turbulent transport over plant canopies was constructed on the basis of the eddy correlation method combined with the gradient method. A test experiment of the system was made over a barley field in May, 1971.

The measured turbulent transport of momentum and carbon dioxide showed realistic diurnal variations. The estimated value of the zero plane displacement was compatible with the published results. Drag coefficient obtained in this experiment was comparable with that observed over paddy field. Its variation with wind speed was reasonable compared with similar measurements over the bare soil. The turbulent fluxes and the transport coefficients estimated by the present method and heat balance method were found to be in fair agreement. These results confirmed that this measuring system is a promising technique.

The measuring system is to be improved by the extension of sampling time of the band pass filter of the analog data analyzer. Further work is now in progress in an attempt to apply the eddy correlation method to the measurements of heat and water vapor transport.

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