SOME TURBULENCE CHARACTERISTICS IN THE SURFACE LAYER OVER A WHEAT FIELD

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INTRODUCTION

The atmospheric turbulence over the plant canopies is important in the exchange process of momentum, heat and carbon dioxide between the vegetation and atmosphere. In recent years, many experimental studies on turbulence have been performed above and within crop canopies under various conditions, e. g., Uchijima and Wright (1964), Högström (1974) and Inoue et al. (1975). However experimental data on basic turbulence statistics are still insufficient.

A series of experiments were conducted by us in 1974 to investigate the characteristics of atmospheric turbulence over some plant canopies. The present paper describes the results of an experiment over a wheat field which is the first of the series. Three components of wind velocity were measured with a set of sonic anemometers, and air temperature and humidity were measured with a thermocouple psychrometer. This instrumentation makes possible the estimation of the horizontal as well as the vertical transport of relevant physical quantities. The acquisition and analysis of the observational data were made by an off-line data acquisition system for micrometeorological observation. The details of the system are described in a separate paper (Maitani and Seo 1976).

METHODS

The experiment was carried out over a wheat field of the Institute at Kurashiki during the 3 hour period from 1200 to 1500 on May 28, 1974. This period had a relatively steady light wind and clear sky. The wind was southerly and the upwind fetch over the wheat field was about 60 m. The crop height was about 80 cm, and the zero-plane displacement was estimated from the crop height as 50 cm. The latter value is within the range given by the formula of Stanhill (1969).

The block diagram of the observation method is shown in Fig. 1. The vertical and horizontal wind velocities w, u_x, u_y at a height of 1.5 m were measured with two sonic anemometers (Kaijodenki Model PAS 112-1 and Model PAS 211-1). Two components of horizontal wind velocity u_x and u_y were transformed into a scalar wind speed u_T and wind direction WD by a vector synthesizer. Fine copper constantan thermocouples of 50μ wire diameter were used for the measurement of dry-bulb temperature (T) and wet-bulb temperature (T_w) at 1.5 m.

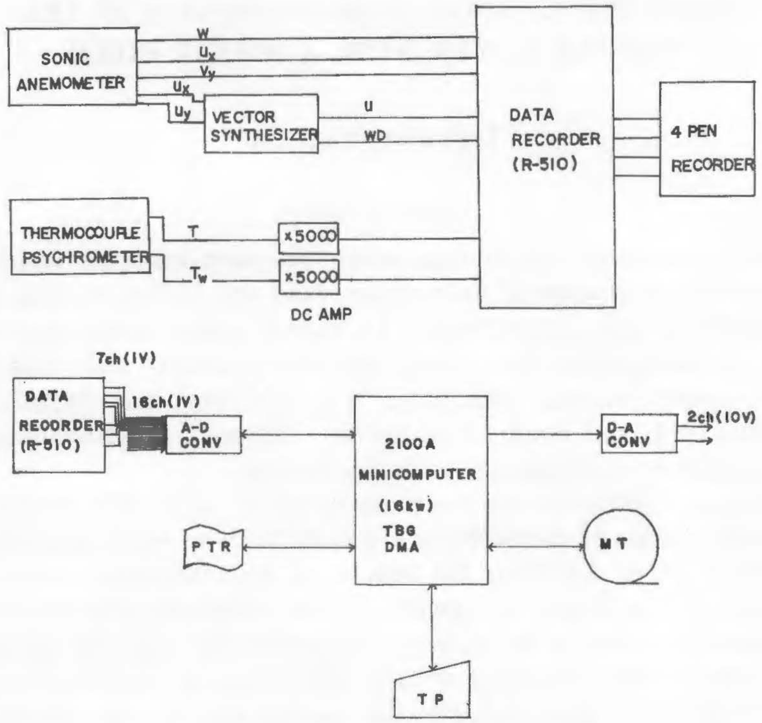


Fig 1. Block diagram of observation.

The signals w, u_x, u_y, u_T, WD, T and T_w were recorded on an analog tape recorder (TEAC R-510). The signals on the analog tape recorder were reproduced and digitized by A/D converter at the sampling rate of 12.5 per second. The data in the experimental period were divided into 12 runs of 15 min duration. The data in digital form were subjected to preliminary processing to provide pertinent physical quantities. In particular, the longitudinal and lateral components of velocity fluctuation (u, v)* were constructed, and the specific humidity q was derived from the T and T_w data. After preliminary data reduction, some turbulence statistics and spectrum were calculated by a YHP 2100A minicomputer. For further details of the data acquisition system, reference is made to another paper (Maitani and Seo 1976).

DEFINITION OF TURBULENCE STATISTICS

Abbrevations used in turbulence statistics in the following section are defined as follows: mean, $\overline{X}$; variance, $\overline{x^2}$; standard deviation, $\sigma_x = \sqrt{\overline{x^2}}$; covariance, $\overline{xy}$; cross correlation coefficient, $r_{xy} = \overline{xy}/\sigma_x\sigma_y$; skewness

* u is positive along the mean wind; v is positive from right to left with the observer facing downwind

factor, $S_x=\overline{x^3}/\sigma_x^3$; flatness factor, $F_x=\overline{x^4}/\sigma_x^4$; intensity of turbulence, $\sigma_x/\overline{X}$; and standard deviation normalized by a characteristic scale x_*, σ_x/x_*, where x and y are deviations from mean values $\overline{X}$ and $\overline{Y}$ and the over bar (-) represents the time mean.

The above-mentioned nondimensional quantities are often examined for stability dependence based on the stability parameter $-z/L$. This parameter is defined as

$$-\frac{z}{L}=\frac{kg\overline{wT}z}{Tu_*^3}\left(1+\frac{0.07Q}{H}\right)$$

where L is the Monin-Obukhov stability length and z, the height of the observation. For convenience, we use $-z/L$ in the place of $-(z-d)/L$, where d is the zero-plane displacement. u_* is the friction velocity, k the von Karman constant, g the gravitational acceleration of the earth, H the sensible heat flux and Q the latent heat flux.

To examine the characteristics of atmospheric turbulence in the frequency domain, power spectrum $S_x(n)$, cospectrum $Co_{xy}(n)$ and spectral correlation coefficient $R_{xy}(n)$ were computed by Tukey's method (Blackman and Tukey 1958). The spectrum and cospectrum are related to the variance $\overline{x^2}$ and covariance $\overline{xy}$ as follows,

$$\overline{x^2}=\int_{n_L}^{n_H}S_x(n)dn \quad , \quad \overline{xy}=\int_{n_L}^{n_H}Co_{xy}(n)dn$$

where n is the frequency in Hz. For example $S_x(n)\ dn$ is the contribution to the variance due to the eddies with frequency range n to $n+dn$. n_H and n_L are the limits of integration. The spectral correlation coefficient $R_{xy}(n)$ is defined as

$$R_{xy}(n)=Co_{xy}(n)/\sqrt{S_x(n)S_y(n)}$$

$R_{xy}(n)$ is a measure of the transfer efficiency associated with the particular scale.

RESULTS AND DISCUSSION

(a) Time variations of turbulence statistics

Time variations of the mean states for the observation period are shown in Fig. 2. During this period, southerly light winds of 0.6 to 1.2 m/s and air temperature of 25 to 30°C continued under clear skies. The air layer was slightly unstable with $-z/L$ ranging between 0.1 and 0.4. The mean turbulent kinetic energy $\overline{e_3}=(\overline{u^2}+\overline{v^2}+\overline{w^2})/2$ varied between 3,000 and 5,000 cm^2/s^2. Thus this period had fairly steady conditions with weak to moderate instability.

In Fig. 3, time variations of the physical quantities relating to momentum transport are shown. The standard deviations of the longi-

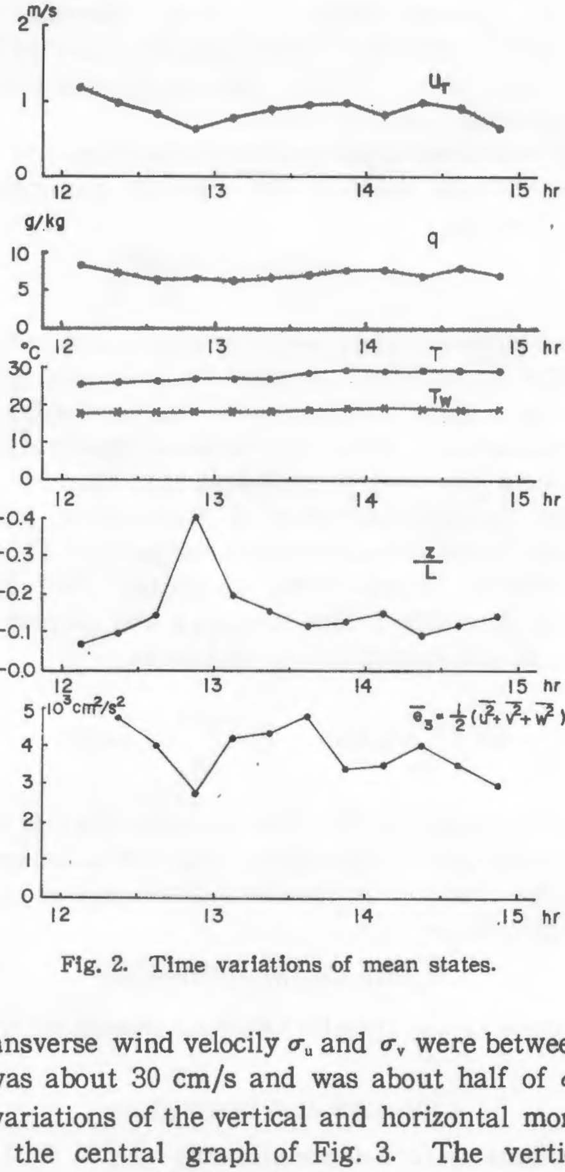


Fig. 2. Time variations of mean states.

tudinal and transverse wind velocily σ_u and σ_v were between 50 cm/s and 70 cm/s. σ_w was about 30 cm/s and was about half of σ_u and σ_v.

The time variations of the vertical and horizontal momentum fluxes are plotted in the central graph of Fig. 3. The vertical flux of the longitudinal momentum $\overline{uw}$ was always downward with values from -400 to -1,000 cm^2/s^2. The vertical flux of the transverse momentum $\overline{vw}$ was positive and its magnitude was smaller than that of $\overline{uw}$. The transverse flux of the longitudinal momentum $\overline{uv}$ was scattered between -400 and 400 cm^2/s^2. The scatter of $\overline{uv}$ is probably a reflection of the large sampling variations of σ_v and σ_u as noted by Lumley and Panofsky (1964) who reported the tremendous variability of σ_v^2 for six contiguous 10-minute periods.

The correlation coefficients relating to the momentum transport are

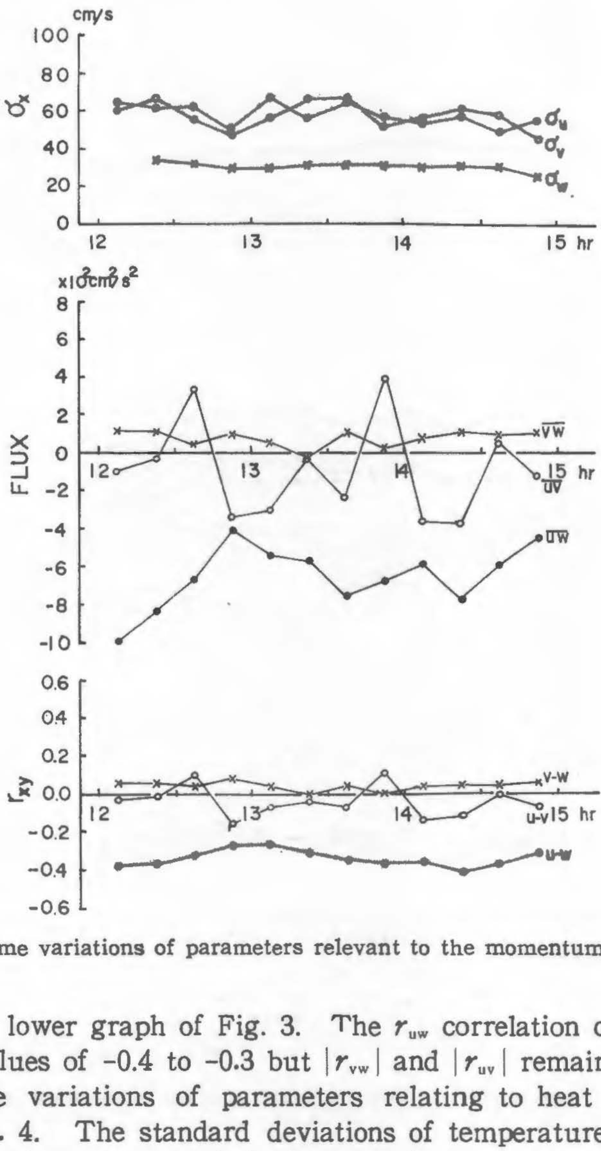


Fig. 3. Time variations of parameters relevant to the momentum transport.

shown in the lower graph of Fig. 3. The r_{uw} correlation coefficient had significant values of -0.4 to -0.3 but $|r_{vw}|$ and $|r_{uv}|$ remained below 0.2.

The time variations of parameters relating to heat transport are shown in Fig. 4. The standard deviations of temperature σ_T remained relatively steady with an indistinct maximum around 13 hr. The standard deviations of specific humidity σ_q fluctuated between 0.6 and 0.8 g/kg.

The vertical flux of sensible heat $H_v = c_p \rho \overline{wT}$ was always upward and was relatively steady. The vertical flux of latent heat $Q_v = l \rho \overline{wq}$ varied between 0.2 and 0.4 cal/cm^{2}min and greater than the values for sensible heat. The total flux $H_v + Q_v$ showed values of 0.4 to 0.6 cal/cm^{2}min.

The longitudinal sensible heat flux $H_h = c_p \rho \overline{uT}$ always had negative values between -0.2 and -0.5 cal/cm^{2}min. This means that sensible heat

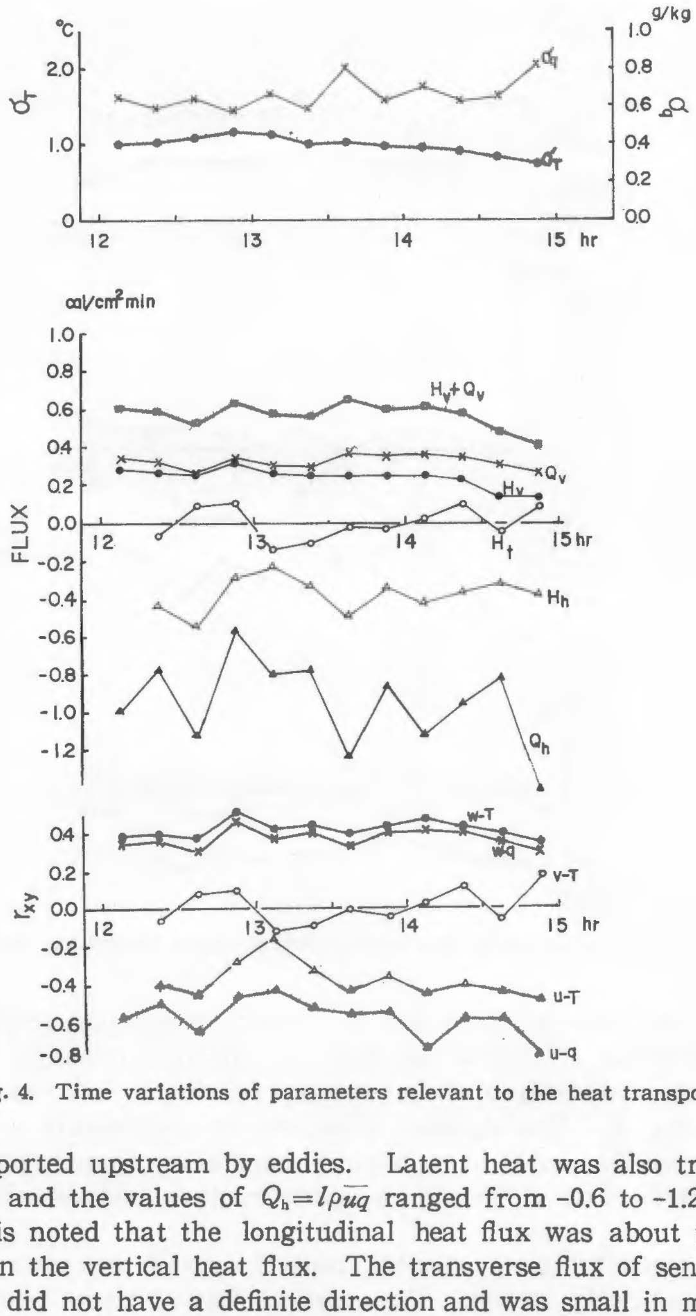


Fig. 4. Time variations of parameters relevant to the heat transport.

was transported upstream by eddies. Latent heat was also transported upstream, and the values of $Q_h = l\rho\overline{uq}$ ranged from -0.6 to -1.2 cal/cm²-min. It is noted that the longitudinal heat flux was about two times larger than the vertical heat flux. The transverse flux of sensible heat $H_t = c_p\rho\overline{vT}$ did not have a definite direction and was small in magnitude.

The correlation coefficients relating to heat transport are shown in the lower section of Fig. 4. The correlation coefficient r_{wT} was slightly larger than that of r_{wq}. The correlation coefficients r_{uT} and r_{uq} were in the negative range of -0.2~-0.5 and -0.4~-0.8, respectively. A comparison of the correlation coefficients shows that in this experiment

$|r_{uq}|>|r_{wT}|\geq|r_{uT}|\geq|r_{wq}|>|r_{vT}|$. Thus, the statistical relationship between u- and q- variations was closest and that between v- and T- variations was worst.

Fig. 5 shows the variations of energy flux and their related quantities. The standard deviations of total kinetic energy and its vertical and horizontal components are shown in the upper part of Fig. 5. Their variations broadly followed the time variations of wind speed and turbulent kinetic energy of Fig. 2. These standard deviations were of the same order as the values of the respective components of turbulent kinetic energy (see, Fig. 2).

The time variations of the kinetic energy fluxes are shown in the middle graph of Fig. 5. Longitudinal kinetic energy flux $\overline{ue_3}$ had positive values ranging from 3,000 to 12,000 cm^3/s^3. The vertical kinetic

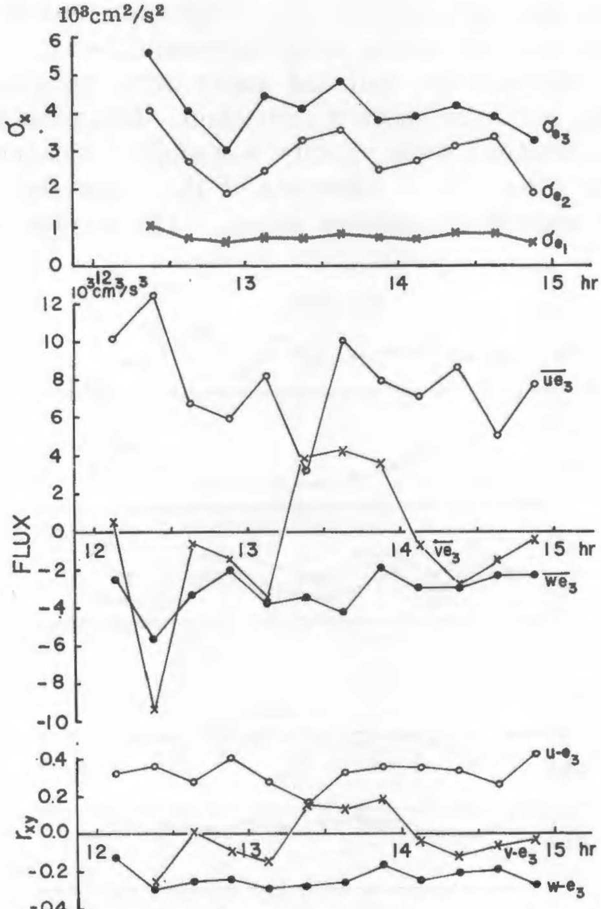


Fig. 5. Time variations of parameters relevant to the kinetic energy transport. $e_1=w^2/2$, $e_2=(u^2+w^2)/2$

energy flux was always downward with negative values of -2,000~-6,000 cm^3/s^3. The transverse flux $\overline{ve_3}$ fluctuated largely around zero. The large fluctuations of $\overline{ve_3}$ probably have an origin in common with that of $\overline{uv}$. The correlation coefficients r_{ue_3}, r_{we_3} and r_{ve_3} were 0.2~0.4, -0.2~-0.3 and -0.2~0.2, respectively.

As mentioned above, in the present study the vertical flux of turbulent kinetic energy was downward. This is in contrast to the results of other investigators. The results of earlier experiments summarized by McBean and Elliott (1975) show that the upward flux under unstable conditions is predominant over relatively smooth surfaces. The downward flux of turbulent kinetic energy might be one of the characteristic features over plant canopies. This will be discussed in detail in a subsequent paper (Maitani 1977).

Time variations of skewness are shown in Fig. 6. The skewness in temperature, specific humidity and longitudinal wind velocity were always positive with the values being between 0.2~1.0. Uchijima and Wright (1964) also reported that the scalar wind velocity had positive skewness in the air layer above a corn plant. It is noted that the skewness of the longitudinal wind velocity was slightly smaller than that of the scalar wind velocity u_T. Skewness of the transverse wind velocity S_v had either positive or negative values. The vertical wind velocity

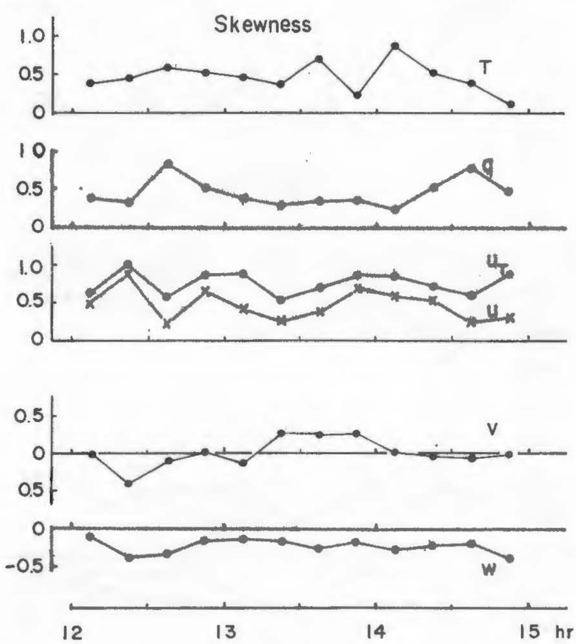


Fig. 6. Time variations of skewness factors of temperature, humidity and wind velocities.

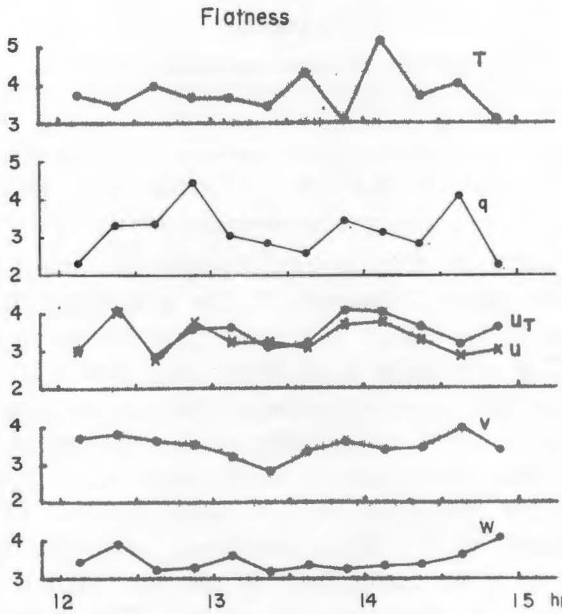


Fig. 7. Time variations of flatness factors of temperature, humidity and wind velocities.

had negative skewness of -0.1 to -0.5. This negative skewness in w is not consistent with the generally accepted fact that the vertical velocity tends to have positive skewness under unstable conditions. The negative skewness in w as well as the positive skewness in u might be related to the mechanism which transports kinetic energy downward.

Time variations of the flatness factor are shown in Fig. 7. The flatness of temperature and the three velocity components were somewhat larger than 3 for the normal distribution. The flatness of specific humidity was scattered around 3. The high flatness implies that the fluctuations over plant canopies are intermittent.

Here it is necessary to consider the accuracy of the estimates of the ensemble averages of statistics presented in this section by time averages. The uncertainty ε in the estimate of the average of variable $f(t)$ can be given as follows (e. g., McBean 1974),

$$\varepsilon=\sqrt{\frac{2z}{\overline{u}\tau}\frac{\overline{\{f(t)-\overline{f(t)}\}^2}}{\overline{f(t)}^2}}=\sqrt{\frac{2z}{\overline{u}\tau}}\frac{\sigma_f}{\overline{f(t)}}$$

where τ is the duration of the averaging time (15 min in the present case) and z is the height (70 cm). Using the mean values of u, σ_f and $f(t)$ during the observation period, the uncertainties of some statistics are estimated. They are given in Table 1. The uncertainty of $\overline{U}$ is about 4 per cent and the uncertainty of $\overline{uw}$ is about 16 per cent.

TABLE 1

Uncertainties of some turbulence statistics

	$\overline{T}$	$\overline{q}$	$\overline{U}$	$\overline{e_3}$	$\overline{uw}$	σ_T	σ_q	σ_u	σ_v	σ_w	σ_{e_3}
$\mathcal{E}$(%)	0.17	0.46	3.3	5.2	16	3.7	3.3	3.5	3.6	3.5	7.5

The uncertainty in the fourth moment is about 2.3 times the uncertainty in the second moment if the averaging time is the same (Lumley and Panofsky 1964). It follows that the accurary of the flatness values of T, q, u, v and w is no better than about 20 per cent. The uncertainty in the skewness estimates is likely to be somewhere between 10 and 20 per cent. The uncertainty of $\overline{we_3}$ can not be determined in this experiment because no data is available on σ_{we_3}. It is estimated to be about 30~40 per cent from data in weak unstable conditions over a paddy field (Maitani 1977). These estimates show that the uncertainty of higher moments is no better than 10 per cent, and it may attain 40 per cent for the third and fourth moments. This makes it difficult to establish the variations of the higher moments with stability.

(b) Nondimensional parameters in weak unstable conditions

In this section, we examine some nondimensional parameters defined

TABLE 2

Nondimensional parameters in weak unstable conditions

Intensity of turbulence	$\sigma_u/\overline{U}_T$=0.67(0.53~0.84), $\sigma_v/\overline{U}_T$=0.69(0.55~0.75), $\sigma_w/\overline{U}_T$=0.36(0.33~0.44)
Nondimensional parameters normalized by u_*	σ_U/u_*=2.40(2.11~2.93), σ_v/u_*=2.45(2.03~2.86) σ_w/u_*=1.27(1.17~1.32), $\sqrt{e_3}/u_*$=2.51(2.18~2.84). $\sigma_T/\lvert T_*\rvert$=1.71(1.30~1.96), $\sigma_q/\lvert q_*\rvert$=2.21(1.54~2.53)
Cross correlation coefficient	r_{uw}=-0.34(-0.41~-0.27), r_{wT}=0.46(0.42~0.55) r_{wq}=0.37(0.30~0.46), r_{we_3}=-0.24(-0.14~-0.29) r_{uT}=-0.39(-0.50~-0.18), r_{uq}=-0.52(-0.75~-0.42) r_{ue_3}=0.31(0.13~0.42), r_{vu}=-0.03(-0.17~0.13) r_{vT}=0.01(-0.14~0.18), r_{ve_3}=-0.02(-0.24~0.19) r_{vw}=0.04(-0.01~0.08)
Skewness factor	S_u=0.50(0.22~0.89), S_v=0.01(-0.40~0.30) S_w=-0.24(-0.39~-0.12), S_T=0.43(0.08~0.73) S_q=0.47(0.29~0.86)
Flatness factor	F_u=3.36(2.74~4.10), F_v=3.45(2.81~4.00) F_w=3.45(3.11~4.08), F_T=3.64(2.63~4.04) F_q=3.38(2.28~4.44)

in section 3. The stability range is limited to the weak unstable conditions ($-z/L < 0.5$). In Table 2, the mean values of nondimensional parameters during the observation period are presented together with the maximum and minimum values. The stability dependence of $\sigma_u/\overline{U}_T$ and $\sigma_v/\overline{U}_T$ is not clear and $\sigma_u/\overline{U}_T = \sigma_v/\overline{U}_T = 0.5 \sim 0.8$. The value of $\sigma_w/\overline{U}_T$ tends to increase slightly with the increase of $-z/L$. These values of turbulence intensity over a wheat field are greater than the values obtained by Maitani (1977) above a rice crop 85 cm high ($\sigma_u/\overline{U}=0.42$, $\sigma_v/\overline{U}=0.40$ and $\sigma_w/\overline{U}=0.22$ at 35 cm above the crop). The difference is presumed to be due mainly to the difference in the aerodynamic characteristics of the surfaces, such as the roughness length z_0 and pliability of the plant.

The values of σ_u/u_*, σ_v/u_*, σ_w/u_*, $\sqrt{e_3}/u_*$, $\sigma_T/|T_*|$ and $\sigma_q/|q_*|$ are shown in Fig. 8 as the function of $-z/L$, where $T_* \equiv -\overline{wT}/u_*$ and $q_* \equiv -\overline{wq}/u_*$. Over the limited range of instability from $-z/L = 0.07$ to 0.5, $\sigma_T/|T_*|$ and $\sigma_q/|q_*|$ tend to decrease with a slope of -1/3 following the local free convection prediction. On the other hand. σ_w/u_* tends to increase with increasing $-z/L$ with a slope of 1/7. This is small compared with 1/3 from the local free convection prediction. The stability dependence of σ_u/u_*, σ_v/u_* and $\sqrt{e_3}/u_*$ is not clearly defined. For $-z/L$

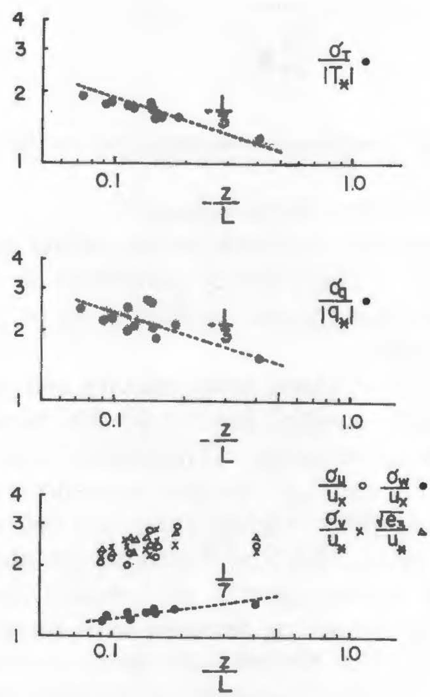


Fig. 8. $\sigma_T/|T_*|$, $\sigma_q/|q_*|$, σ_u/u_*, σ_v/u_*, $\sqrt{e_3}/u_*$ and σ_w/u_* v.s. $-z/L$.

$=0.1$, the values of the nondimensional parameters are $\sigma_T/|T_*|=1.8$, $\sigma_q/|q_*|=2.4$, $\sigma_u/u_*=2.2$, $\sigma_v/u_*=2.3$, $\sqrt{\overline{e_3}}/u_*=2.5$ and $\sigma_w/u_*=1.2$. These values agree fairly well with the values estimated from the regression lines obtained by McBean (1971) ($\sigma_T/|T_*|=1.5$, $\sigma_u/u_*=2.3$, $\sigma_v/u_*=2.05$ and $\sigma_w/u_*=1.45$), who analyzed data observed over an unused airport (grass height 4~8 cm). The values of $\sigma_T/|T_*|$ and $\sigma_q/|q_*|$ are not significantly different from $\sigma_T/|T_*|=2.0$ and $\sigma_q/|q_*|=2.2$ obtained by Högström and Smedman-Högström (1974) over an agricultural site (Marsta, Sweden).

The correlation coefficients relevant to the vertical fluxes are plotted against $-z/L$ in Fig. 9. The correlation coefficients r_{wT} and r_{uw} tended to increase slightly with increasing instability. The other correlation coefficients showed no evidence of stability dependency over the instability range examined. The dependence of the skewness and flatness factors on stability was not evident. It is noted that the skewness of w was negative in weak unstable conditions, as mentioned previously.

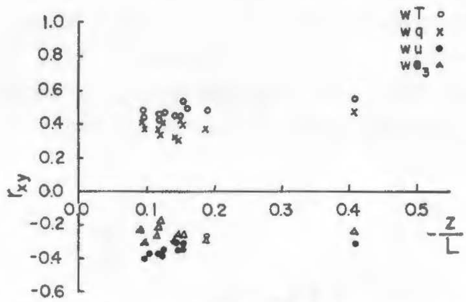


Fig. 9. Correlation coefficients relevant to the verticial fluxes v.s. $-z/L$.

(c) Spectral characteristics of turbulence

The results of spectral analysis in the period of 1300-1330 are presented in this section. The stability parameter in the period was $-z/L=0.15$. The obtained spectra are considered to be typical for the whole period of the experiment.

The power spectra of three wind velocity components are shown in Fig. 10. The velocity spectra for $n>0.5$ Hz have a slope of -5/3 as expected in the inertial subrange. The ratios $S_w(n)/S_u(n)$ and $S_v(n)/S_u(n)$ are shown in Figs. 11a and 11b. In the frequency range above 1 Hz, the ratio $S_w(n)/S_u(n)$ is slightly higher than 4/3 as expected in isotropic turbulence but the ratio $S_v(n)/S_u(n)$ fluctuates around 4/3.

The normalized power spectra of temperature and humidity are shown in Fig. 12. Both spectra decrease with increasing frequency following the -5/3 law. The temperature spectrum falls off more rapidly than the q-spectrum in the frequency range higher than 1 Hz. It is not clear whether this fall-off is due to the instrumental effects or not.

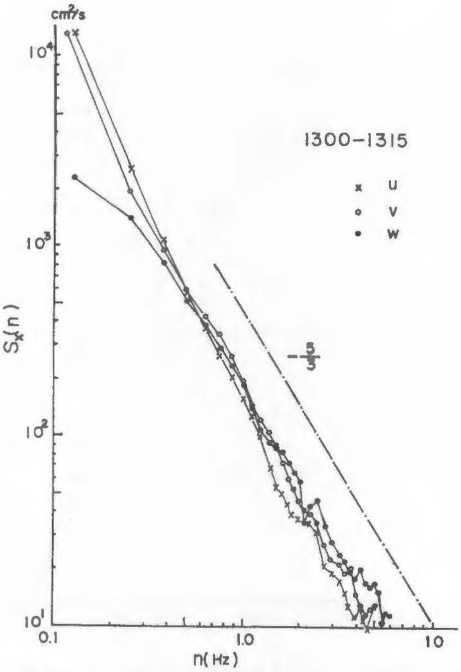


Fig. 10. Power spectra of wind velocity components.

Fig. 11a. $S_v(n)/S_u(n)$ v.s. the frequency n.

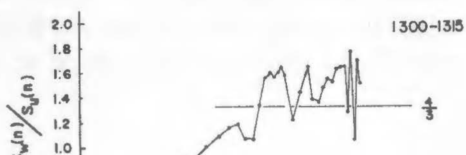


Fig. 11b. $S_w(n)/S_u(n)$ v.s. the frequency n.

Cospectra of vertical fluxes of momentum, sensible heat and moisture are presented in Fig. 13. The cospectra are obtained by composing the results of the spectral analysis of the data with averaging time of 0.08 and 0.8 sec. These three cospectra have similar shapes over the analyzed range of frequency, showing a peak near 0.15 Hz. Significant contributions to the total fluxes can not be seen for $n > 1.0$ Hz, where the inertial subrange is considered to exist.

Spectral correlation $R_{uw}(n)$ increases with increasing n to a peak near $n = 0.05$ Hz; it remains constant for 0.05∼0.2 Hz and decreased with

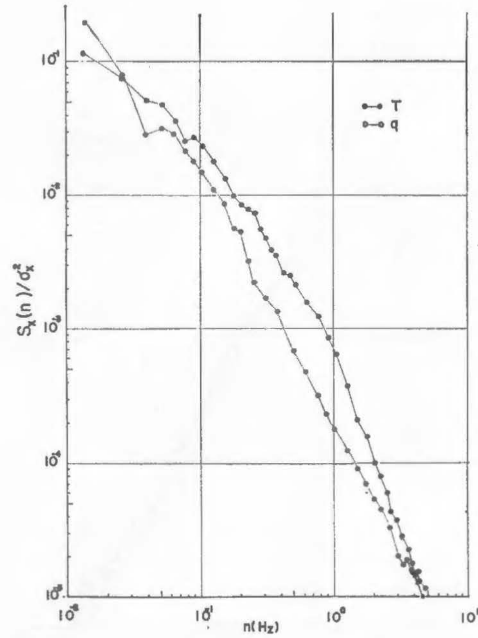
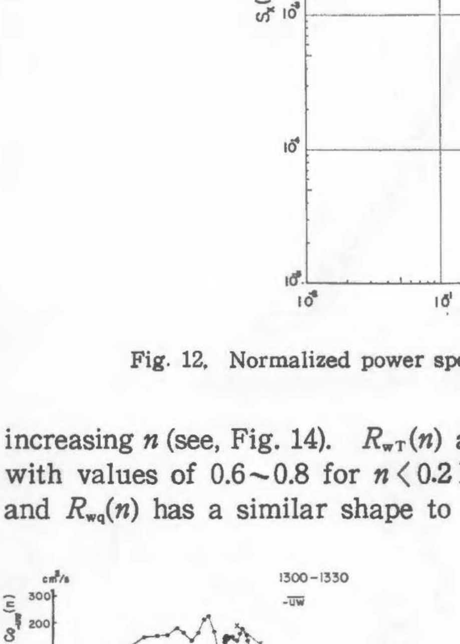


Fig. 12. Normalized power spectra of temperature and humidity.

increasing n (see, Fig. 14). $R_{wT}(n)$ and $R_{wq}(n)$ are approximately constant with values of 0.6~0.8 for $n < 0.2$ Hz. At higher n, the fall-off of $R_{wT}(n)$ and $R_{wq}(n)$ has a similar shape to that of $R_{uw}(n)$.



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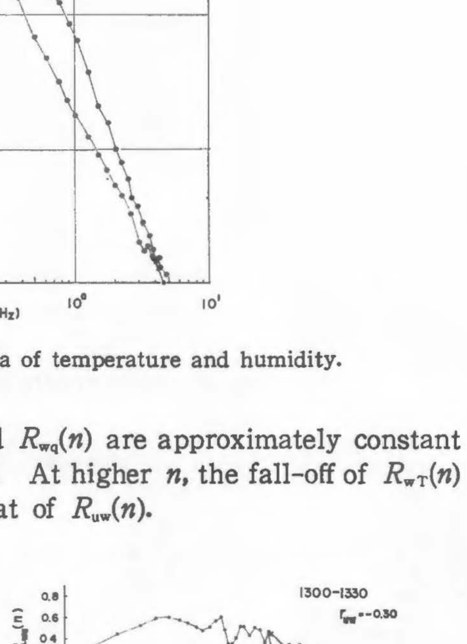

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Fig. 13. Cospectra of vertical fluxes of momentum, sensible heat and moisture. averaging time; (×) 0.08 sec, (•) 0.8 sec

Fig. 14. Spectral correlation coefficients of vertical fluxes of momentum, sensible heat and moisture. averaging time; (×) 0.08 sec, (•) 0.8 sec

In Fig. 15, the cospectrum and spectral correlation coefficient between w and e_3 are plotted. The cospectrum $nCo_{we_3}(n)$ is downward through the analyzed frequency range except for the high frequency end. It decreases with increasing n to a minimum value near 0.15 Hz and then decreases with increasing n. The spectral correlation coefficient $R_{we_3}(n)$ is almost -0.3 at frequencies lower than 0.5 Hz and decreases to zero at a higher frequency range.

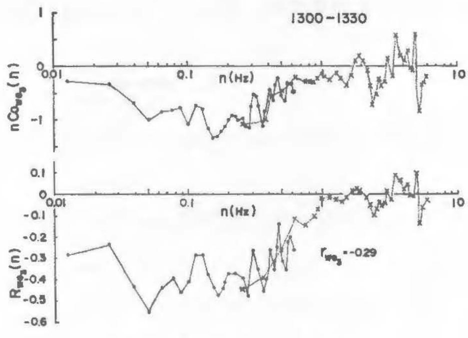

Fig. 15. Cospectrum and spectral correlation coefficient of vertical flux of turbulent kinetic energy. averaging time; (×) 0.08 sec, (•) 0.8 sec

The downward flux of kinetic energy through the frequchcy range in the present observation is in contrast to the cospectrum with an upward energy flux obtained by McBean and Elliott (1975), who analyzed data observed at a height of 5.77 m above rolling prairie grass under unstable conditions.

Spectral correlation coefficients $R_{ue_3}(n)$ and $R_{uT}(n)$ are shown in Fig. 16. It is noted that $R_{uT}(n)$ and $R_{ue_3}(n)$ have significant values throughout the analyzed frequency range, corresponding to the significant r_{uT} and r_{ue_3}. $R_{ue_3}(n)$ increases with increasing n to a peak near $n=0.05$ Hz. It

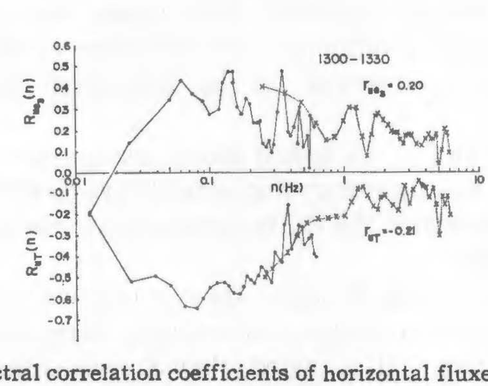

Fig. 16. Spectral correlation coefficients of horizontal fluxes of sensible heat and kinetic energy. averaging time; (×) 0.08 sec, (•) 0.8 sec

remains nearly constant at 0.3~0.5 in the frequency range for 0.05~0.5 Hz and then decreases gradually with increasing *n*. $R_{uT}(n)$ and $r_{ue_s}(n)$ are roughly symmetric with respect to the zero line.

The spectral correlation coefficients of transverse fluxes $R_{uv}(n)$, $R_{wv}(n)$ and $R_{ve_s}(n)$ are scattered around zero (Fig. 17). The absolute values of these three spectral correlation coefficients are below 0.2 throughout the frequency range. These results indicate that significant contributions are not present to the transverse fluxes throughout the analyzed frequencies.

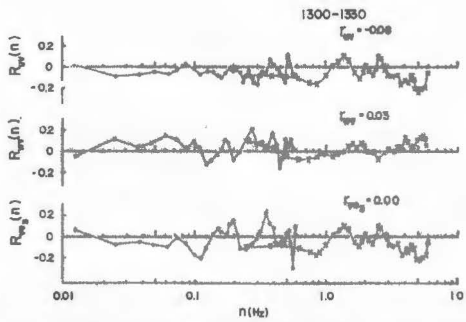

Fig. 17. Spectral correlation coefficients of transverse fluxes of momentum and kinetic energy. averaging time; (×) 0.08 sec, (•) 0.8 sec

CONCLUSIONS

A field experiment was undertaken over a wheat field as part of a study on characteristics of atmospheric turbulence over plant canopies. The off-line data acquisition system, which was developed for micrometeorological observations, was used for data acquisition and data analysis. The observation was made under unstable conditions in the afternoon. The observational results are summarized as follows,

(1) Correlation coefficients r_{wT} and r_{wq} were always positive and r_{uw}, r_{uT} and r_{uq} were always negative. This agrees with the results expected under weak unstable conditions. On the other hand, correlation coefficients r_{uv}, r_{vT} and r_{ve_s} relevant to the transverse fluxes were scattered around the zero.

(2) The vertical flux of turbulent kinetic energy was always downward, and longitudinal kinetic energy flux was always downstream. The downward flux may be one of the characteristic features in the surface layer over plant canopies.

(3) Skewness S_T, S_q and S_u were always positive with values of 0.2~1.0 but they showed no evidence of stability dependence. S_v was either positive or negative. It is noted that S_w was always negative under unstable conditions.

(4) Over limited unstable conditions of $-z/L < 0.5$, nondimensional parameters follow the Monin-Obukhov similarity theory. $\sigma_T/|T_*|$ and $\sigma_q/|q_*|$ tended to decrease with an increase of $-z/L$ following the local free convection prediction.

(5) Spectra of u, v, w, T and q decreased with a slope of -5/3 in the high frequency range. Cospectra and spectral correlation coefficients of vertical fluxes of momentum, sensible heat and moisture had similar shapes through the analyzed frequency range.

(6) The cospectrum and spectral correlation coefficient of vertical kinetic energy flux were negative in the low frequency range below 1 Hz, corresponding to the downward energy flux.

(7) The absolute values of the spectral correlation coefficients of transverse fluxes were below 0.2 throughout the analyzed frequency range, corresponding to the small correlation coefficients.

These results are generally consistent with the results obtained by other investigators over plant canopies, though they involved some peculiar phenomena such as downward energy flux. After the experiment reported here, further observations were conducted over various kind of plant canopies and these data will be reported elsewhere in the future.

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