VERTICAL TRANSPORT OF TURBULENT KINETIC ENERGY WITHIN PINE WOODS

Toshihiko MAITANI

Turbulent flow within plant canopies and their boundary regions dominates the exchange processes between vegetation and atmosphere. Comprehensive studies have been made of wind behavior inside plant conopies (e.g., Uchijima and Wright 1964, Meroney 1968, Isobe 1972, Inoue et al. 1975) which have provided a highly complex picture of the process. However, a definite need still exsists for further investigations on the turbulence characteristics of the flow in order to understand the exchange processes. In 1974, an observation on atmospheric turbulence within pine woods were made (Seo et al. 1975).

The present author has an interest on budget of turbulent kinetic energy, because it shows the relationship between some factors controlling the motion of the atmosphere within plant canopies. Except for the study by Lesnik (1974) on energy budget within a pine forest, not much data are available on the transportation of turbulent kinetic energy within plant canopies. It is the main purpose of the present paper to examine some of the characteristics of turbulent kinetic energy flux within a small pine forest, using direct measurements by sonic anemometers.

METHOD

(1) Vertical flux of kinetic energy

The vertical flux of total kinetic energy per unit mass E can be expressed as follows

$$\overline{wE}=\overline{\tfrac{1}{2}\ w\{(\overline{U}+u)^2+v^2+w^2\}}=\overline{wu}\overline{U}+\overline{\tfrac{1}{2}\ w(u^2+v^2+w^2)}=-u_*^2\overline{U}+\overline{we_3} \quad (1)$$

where $\overline{U}$ is the mean wind velocity and u, v and w are longitudinal, transverse and vertical components of fluctuating wind velocities, respectively. Time average is represented by the overbar. The friction velocity is defined as $u_*=\sqrt{-\overline{uw}}$ and turbulent kinetic energy per unit mass as $e_3=(u^2+v^2+w^2)/2$. The first term$(-u_*^2\overline{U})$ on the right hand side in eq (1) is the vertical flux of the kinetic energy of mean flow and the second term $(\overline{we_3})$ is the vertical flux of turbulent kinetic energy. The flux can be easily measured by sonic anemometry (Maitani and Mitsuta 1967).

(2) Field experiment

The field experiment was conducted in pine woods of the Forestry Experiment Station of Okayama Prefecture in October, 1974. The average height of the pine trees was about 5.5 m and the foliage was thick 3 m to 5 m from the ground. The observation pole was erected at mid-slope of the hill with a slope of about 5 degrees in an east-west direction and about 3 degrees in a north-south direction. The fetch was only 50 ~ 60 meters. Sonic anemometers for measuring three dimensional wind velocity were mounted at a height of 4 m above ground. The one dimensional anemometer for measuring vertical velocity was mounted at 7 m height, which was higher than the pine trees by about 1.5 m. Fine copper constantan thermocouple thermometers of 50 μm in diameter were installed near the sensing path of the vertical wind to measure the dry- and wet-bulb temperatures at 7 m height. The output signals from the sensors were recorded on magnetic tape and monitored on a 4-pen recorder. The playback signals from the tape were digitized and processed at the laboratory by an off-line data acquisition system for micrometeorological observation (Maitani and Seo 1976). The sampling rate was 6 per second and the sampling duration of a single run was 30 minutes.

RESULTS AND DISCUSSIONS

The experiment was undertaken at daytime for 6 hours from 1000 to 1600 on October 23, 1974. The mean wind speed at 4 m was about 1 m/s and a west wind prevailed in the first half of the observation period and then the wind direction shifted north. The slope of the site gradually descended windward. Table 1 shows some of the main results observed by sonic anemometers.

The mean vertical wind velocity w at 4 m was always positive as seen in the table. This upward air flow is considered to be due to the slope of the observation site. Fig. 1 shows the inclination of the stream line as a function of the wind direction. The dependency of inclination on wind direction is seen from the figure. When the wind was from the west, the inclination angle was maximum, with a mean angle of about 10 degrees. Selection of the coordinate system appropriate for such an inclining flow is the subject of re-examination, and the coordinate system taken here refers to the mean stream line. Table 1 shows the turbulence statistics in the coordinate system relative to the stream-line, together with those of the traditional true horizontal coordinate system. The mean wind speed and root mean squares of fluctuations of wind velocities (σ_u and σ_w) are not much different in both coordinate systems. The transverse wind velocity v and the turbulent kinetic energy e_3 are invariant for transformation of the coordinate. The values of u_* and $\overline{we_3}$ to the coordinate system rela-

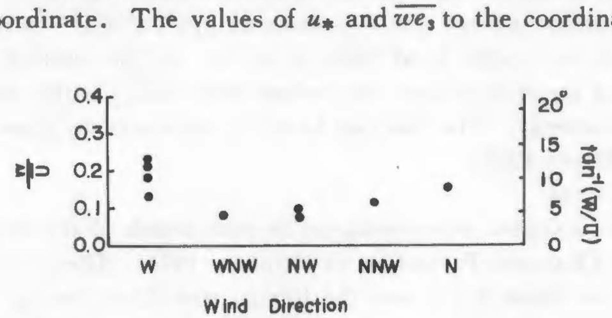

Fig. 1. The inclination of mean stream line as a function of wind direction.

TABLE 1

Main results observed in pine woods of the Forestry Experiment Station of Okayama Prefecture in October, 1974.

Time	1015 ~ 1045	1045 ~ 1115	1115 ~ 1145	1145 ~ 1215	1215 ~ 1245	1245 ~ 1315	1315 ~ 1345	1345 ~ 1415	1415 ~ 1445
$\overline{U}$(cm/s)	102	126	125	113	97	77	67	66	87
wind direction	*W*	*W*	*W*	*W*	*WNW*	*NW*	*NW*	*NNW*	*N*
$\overline{W}$(cm/s)	22	24	22	14	8	6	6	7	13
$\overline{W}/\overline{U}$	0.22	0.21	0.18	0.12	0.08	0.07	0.09	0.11	0.15
$\overline{U}_s$(cm/s)	104	128	127	114	97	77	67	66	88
σ_w(cm/s)	45	51	56	49	49	44	44	49	60
σ_{w_s}(cm/s)	48	56	59	52	51	45	44	51	64
σ_u(cm/s)	65	83	83	76	62	48	47	52	74
σ_{u_s}(cm/s)	62	80	81	74	61	47	46	50	70
σ_v(cm/s)	72	66	73	55	59	62	56	52	56
σ_{v_s}(cm/s)	72	66	73	55	59	62	56	52	56
e_3(cm^2/s^2)	5.7	6.9	7.7	6.6	4.8	4.0	3.6	3.9	6.1
e_{3_s}(cm^2/s^2)	5.7	6.9	7.7	6.6	4.8	4.0	3.6	3.9	6.1
u_*(cm/s)	22	29	24	30	29	23	20	27	38
u_{*_s}(cm/s)	30	40	35	36	31	24	20	27	40
$\overline{we_3}$($\times 10^5$cm^3/s^3)	−1.02	−1.47	−1.29	−1.18	−1.24	−1.09	−0.89	−1.30	−2.37
$\overline{we_{3_s}}$($\times 10^5$cm^3/s^3)	−1.58	−2.51	−2.11	−1.64	−1.41	−1.21	−0.98	−1.49	−3.01
$-\frac{1}{2}(\overline{w_7^3}-\overline{w_4^3})$($\times 10^5$cm^3/s^3)#	−0.47	−1.41	−1.99	−1.90	0.15	−0.59	−1.31	−1.02	−2.70
$-\frac{1}{2}(\overline{w_7^3}-\overline{w_4^3})/u_*^3$#	−4.41	−5.78	−14.4	−7.04	0.62	−4.85	−16.4	−5.18	−4.93

Subscript *s* signifies the quantity in the coordinate referred to the mean stream line. # subscript 7 and 4 represent observation heights of 7 m and 4 m, respectively.

tive to the stream line are greater than those to the true horizontal frame. The difference in the latter half of the observation period is relatively small. In any case, it is difficult to decide which value is more significant. In the following discussion, the coordinate system by traditional definition relative to the true horizontal is used, because the flux perpendicular to the stream line is generally difficult to define, as the inclination varies with height.

1) Vertical flux of turbulent kinetic energy

Fig. 2 shows the time variation in vertical flux of turbulent kinetic energy, as well as wind velocity and turbulent kinetic energy. In this period over the pine woods conditions were somewhat unstable, with partly cloudy skies. As clearly seen in the figure, turbulent kinetic energy was transported downward throughout this period, except for quite rare upward flux. The downward

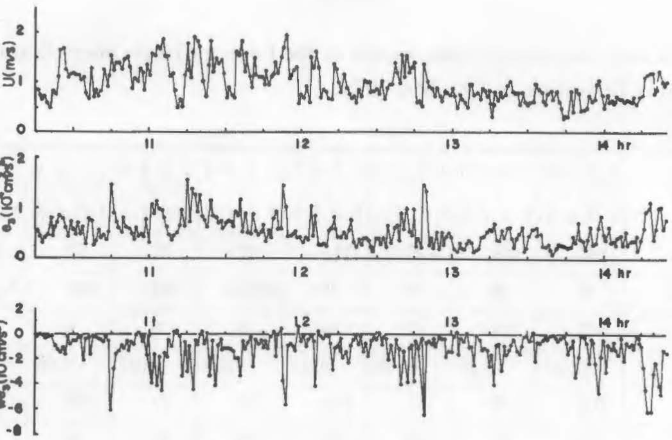

Fig. 2. Time series of wind velocity, turbulent kinetic energy and its vertical flux for about 4 hours from 1015 to 1420 on October 23, 1974.

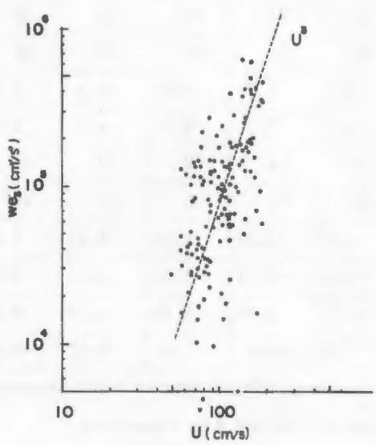

Fig. 3. Relationship between energy flux and wind velocity. Each value represents one minute average.

energy flux tended to increase with increasing wind velocity, or increasing turbulent kinetic energy. Fig. 3 shows the relationship between energy flux and wind velocity. The energy flux increases rapidly with increasing wind velocity showing the relation $\overline{we_3} \propto \overline{U}^3$. This relationship is similar to results obtained over a paddy field under nearly neutral conditions (Maitani 1977). Fig. 4 shows the relationship between energy flux and turbulent kinetic energy. The relation $\overline{we_3} \propto e_3^{3/2}$ is seen in the figure in spite of the large scatter for $e_3 < 5000$ cm^2/s^2.

Fig. 5 compares turbulent kinetic energy flux and each component of turbulent kinetic energy flux. Each component of turbulent kinetic energy flux is negative and is roughly proportional to turbulent kinetic energy flux. The mean ratios of $\overline{wu^2}/2/\overline{we_3}$, $\overline{wv^2}/2/\overline{we_3}$ and $\overline{ww^2}/2/\overline{we_3}$ are 0.41, 0.25 and 0.34, respectively. Thus, it appears that one-third of the transport is due to the vertical component. This result is different from the one-tenth obtained over a paddy field (Maitani 1977) but shows a close agreement with results observed by Wyngaard and Coté (1971) over stubble fields in Kansas, in spite of the reverse direction of energy flux.

The vertical flux of kinetic energy of mean flow and turbulent kinetic energy flux are compared in Fig. 6. For comparison, data obtained in unstable conditions over some plant canopies are plotted in this figure (Maitani 1977). The ratio $\overline{we_3}/\overline{uw}\overline{U} = 2.1$ observed within pine woods is greater than the same ratio over plant canopies. As the divergences of these two fluxes at fixed height are the main terms in the energy budget equation, this implies that the transport of turbulent kinetic energy plays an important role as the source or sink of turbulent kinetic energy within plant canopies.

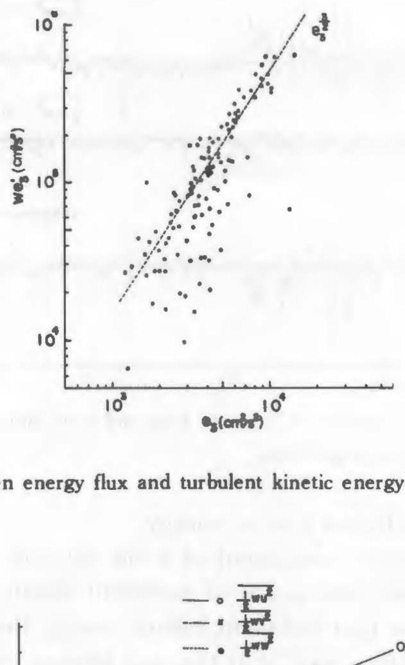

Fig. 4. Relationship between energy flux and turbulent kinetic energy Each value represents one minute average.

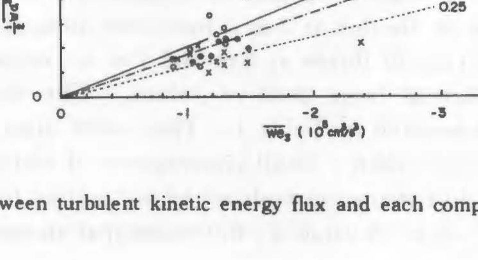

Fig. 5. Comparison between turbulent kinetic energy flux and each component of turbulent kinetic energy flux.

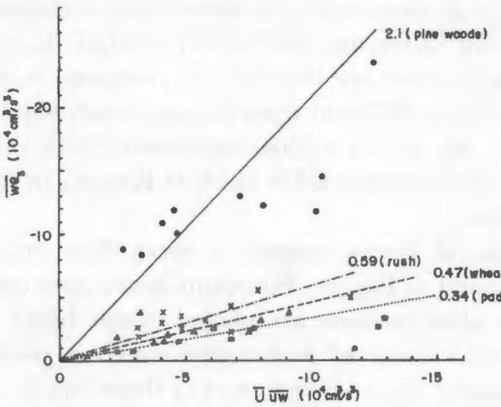

Fig. 6. Comparison between vertical flux of kinetic energy of mean flow and turbulent kinetic energy flux.

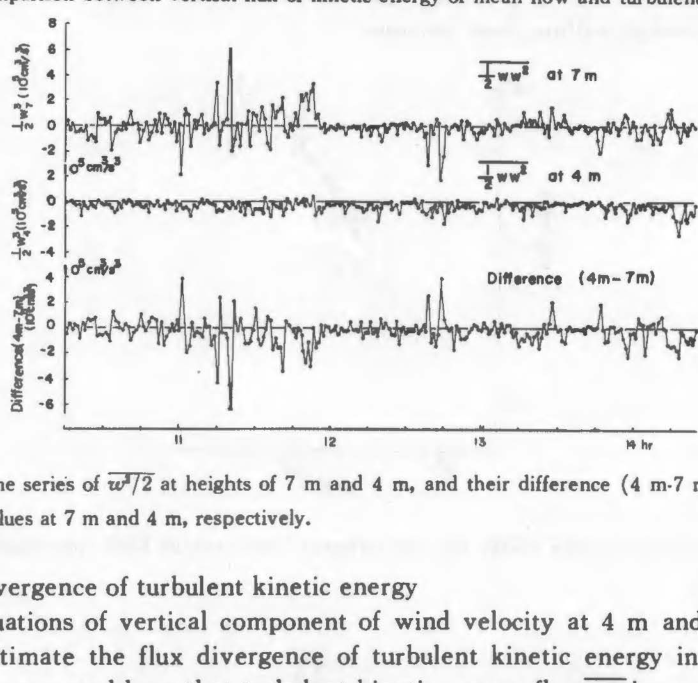

Fig. 7. Time series of $\overline{w^3/2}$ at heights of 7 m and 4 m, and their difference (4 m-7 m). $\overline{w^3_7}$ and $\overline{w^3_4}$ represent values at 7 m and 4 m, respectively.

2) Flux divergence of turbulent kinetic energy

Fluctuations of vertical component of wind velocity at 4 m and 7 m were used to estimate the flux divergence of turbulent kinetic energy in crown top layer. It is assumed here that turbulent kinetic energy flux $\overline{we_3}$ is proportional to one-dimensional energy flux $\overline{ww^2/2}$ at the two heights of 7 m and 4 m. Fig. 7 shows the time series of $\overline{ww^2/2}$ at the two heights of 7 m and 4 m and their difference. The sense of the flux at 7 m is indefinite although at 4 m it is almost downward. The difference of fluxes at 4 m and 7 m are negative in spite of the intermittent appearance of large positive values. The divergence estimated from $\overline{ww^2/2}$ is also presented in Table 1. They were always negative, except for the period 1215-1245, when a small convergence of turbulent kinetic energy was observed. The divergence normalized by u_*^3 varies from 0.62 to -16.4, with a mean value of -6.9. A value of -6.9 means that an appreciable amount of

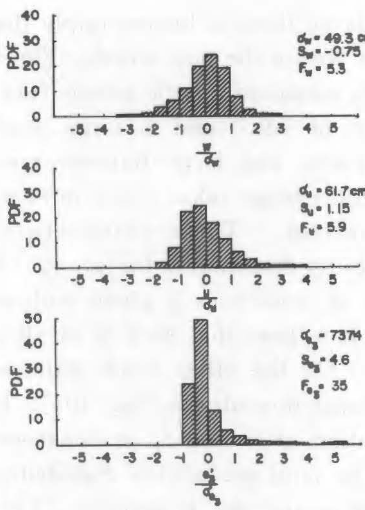

Fig. 8. Probability density of w, u and e_3' at 4 m. PDF represents a probability density function.

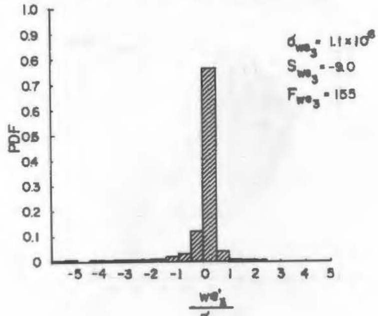

Fig. 9. Probability density of instantaneous turbulent kinetic energy flux we_3'. PDF represents a probability function.

turbulent kinetic energy diverges from the crown top layer between 4 m and 7 m. This agrees with the results by Lesnik (1974), who showed that the crown top layer in a pine forest was a divergence zone.

3) Characteristics of turbulent kinetic energy flux

The transport mechanism of turbulent kinetic energy was studied. Fig. 8 shows the probability density of w, u and e_3' at 4 m for the time interval 1215-1245, where e_3' is the fluctuation of turbulent kinetic energy. The frequency distribution of vertical wind velocity is negatively skewed, but the frequency distributions of u and e_3' are positively skewed. The skewness factor of e_3' is a large value of 4.6. It is noted that the flatness factors of w, u and e_3 are greater than 3 in Gaussian distribution. The pronounced asymmetry of the frequency distribution of wind velocity fluctuations is consistent with the results of Seginer et al. (1976), who measured wind velocity fluctuations above and within a model plant canopy. The large flatness factors imply that the fluctuations were intermittent in the air layer within the pine woods. Fig. 9 shows the probability distribution of instantaneous turbulent kinetic energy flux. The figure illustrates a large negative skewness of −9.0 and a large flatness of 155. These large negative skewness factor and large flatness factor indicate that the transport of turbulent kinetic energy takes place intermittently in a few large bursts in a downward direction. These characteristics are more distinctly observed in the joint probability distribution for (w, e_3') and (w, we_3') (Fig. 10a and 10b). The probability of occurrence is given with isopleths of 0.005, 0.01, 0.02, 0.04, 0.08 and 0.16. It follows that 99.9 % of all occurrence are included within the outermost line. On the other hand, extremely large values of e_3' exceeding 4σ, occur in the large downdrafts (Fig. 10a). It can be also seen from this figure that the correlation of w and e_3' is negative, corresponding to the downward energy flux. The joint probability distribution for (w, we_3') shows that the correlation between w and we_3' is positive. The positive correlation of

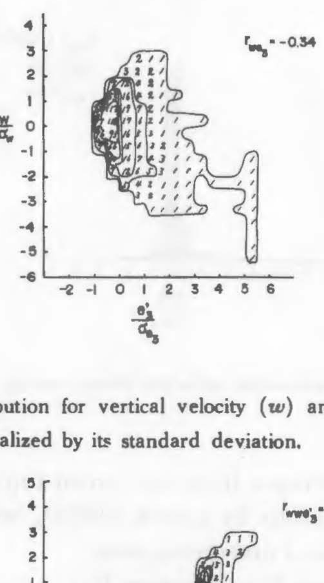

Fig. 10a. Joint probability distribution for vertical velocity (w) and fluctuation of turbulent kinetic energy (e_3'). Each value is normalized by its standard deviation.

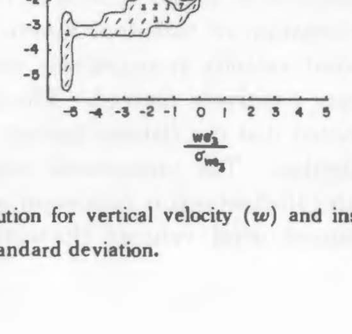

Fig. 10b. Joint probability distribution for vertical velocity (w) and instantaneous energy flux (we_3). Each value is normalized by its standard deviation.

0.67 implies that the transport of turbulent kinetic energy is closely related with fluctuations of vertical velocity and that the downward transport of turbulent kinetic energy is mainly by downdrafts. However the correlation coefficient of 0.67 is noted, because the air flow within plant canopies is generally considered to be highly turbulent.

The flux-vertical velocity distribution (Fig. 11) is constructed from the joint probability distribution of Fig. 10a to examine the contributions to vertical flux at different vertical velocities. The vertical axis is the percentage of $\overline{we_3}$'

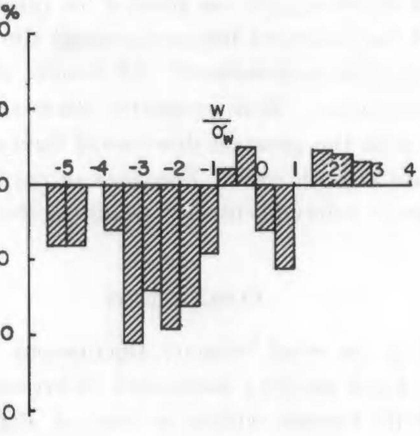

Fig. 11. Contributions to turbulent kinetic energy flux at different vertical velocities.

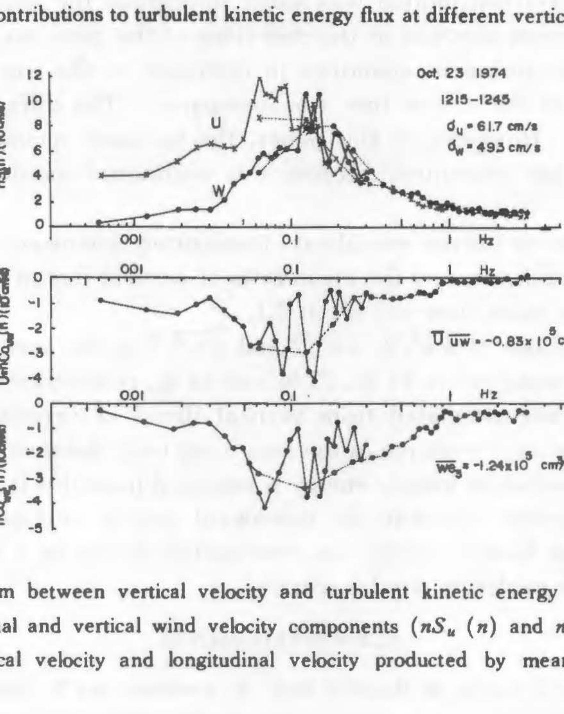

Fig. 12. Cospectrum between vertical velocity and turbulent kinetic energy ($nCo_{we_3}(n)$), power spectra of longitudinal and vertical wind velocity components ($nS_u(n)$ and $nS_w(n)$) and cospectrum between vertical velocity and longitudinal velocity producted by mean wind velocity ($\overline{U}$x $nCo_{uw}(n)$).

transported at different vertical velocities. The figure shows that most of the downward energy flux is transported by downdrafts. The range $-3.5 < w/\sigma_w < -1.0$ particularly contributes largely to downward energy. The portion of flux transported by updrafts is very small, since the distribution is negative for small updrafts and positive for large updrafts. Downdrafts being more efficient for downward energy flux than updraft has also been pointed out in analysis of data over a paddy field (Maitani 1977).

The cospectrum between vertical velocity and turbulent kinetic energy is computed for the same case (Fig. 12). In the figure, the power spectrum of u and the cospectrum of $\overline{U} \times nCo_{wu}(n)$ are plotted for reference. The results indicate that over most of the analyzed frequency range the cospectrum is negative, showing that the energy flux is downward. Of course, the flux of kinetic energy of mean flow is also negative. Both cospectra show similar shapes throughout the frequency range, with the greatest downward fluxes in the range of 0.05 ~ 0.5 Hz and small values at both ends. The peak of cospctrum between w and e_t is considered to be closely related with the peaks of the power spectra of u and w.

CONCLUSIONS

Observational data on wind velocity fluctuations in a small pine forest (average tree height of 5.5 meters) were used to investigate the vertical transport of turbulent kinetic energy within a layer of vegetation. A significant amount of mean vertical motion was found throughout the observation period, because the examined site was at the mid-slope of the pine woods. The difference between the turbulent quantities in reference to the true horizontal line and in reference to the stream line was compared. The difference was sometimes very large. However, in this paper, the turbulent quantities to the true horizontal plane are presented, because this traditional coordinate can be defined easily.

Turbulent kinetic energy was always transported downward at a height of 4 m in the vegetation layer, and the mean ratio of vertical flux of turbulent kinetic energy and that of mean flow was about 2.1.

The contributions of $\overline{wu^2/2}$, $\overline{wv^2/2}$ and $\overline{ww^2/2}$ to the vertical transport of turbulent kinetic energy were 41 %, 25 % and 34 %, respectively.

Flux divergence estimated from vertical fluxes of vertical wind velocity components was always negative in the crown top layer between 4 m and 7 m. This means that turbulent kinetic energy is exported from this layer.

Downdrafts were efficient for downward energy transport within pine woods. Turbulent kinetic energy was transported mainly in a frequency range of 0.05 ~ 0.5 Hz in moderate wind conditions.

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REFERENCES

Inoue, K., Uchijima, Z., Horie, T. and Iwakiri, S. 1975. Studies of energy and gas exchange within crop canopies (10). J. Agric. Met. (Tokyo), 31 (2), 71-82.

Isobe, S. 1972. A spectral analysis of turbulence in a corn canopy. Bull. Natl. Inst. Agric. Sci. (Japan), Ser. A, No 19, 101-113.

Lesnik, G. E. 1974. Results of measurements of the turbulent energy balance components in a layer of vegetation. Izv. Acad. Sci. USSR, Atmospheric and Oceanic Physics. 10 (6), 400-401.

Maitani, T. and Mitsuta, Y. 1967. A direct mesurement of vertical transport of turbulent kinetic energy in the air layer near the ground with sonic anemometers. Special Contr. Geophys. Inst. Kyoto Univ., No. 7. 71-81.

Maitani, T. and Seo, T. 1976. An off-line data acquisition system for micrometeorological observation. Nogaku Kenkyu, 55 (4), 215-232 (in Japanese).

Maitani, T. 1977. Vertical transport of turbulent kinetic energy in the surface layer over a paddy field. Boundary-Layer Meteorol. 12, 405–423.

Meroney, R. N. 1968. Characteristics of wind and turbulence in and above model forest. J. Appl. Met. 7, 780-788.

Seginer, I., Mulhearn, P. J., Bradley, E. F., and Finningan, J. J. 1976. Turbulent flow in a model plant canopy. Boundary-Layer Meteorol., 10, 423–453.

Seo, T., Ohtaki, E. and Maitani, T. 1975. The observation of turbulent flow within pine woods (Unpublished manuscript).

Uchijima, Z. and Wright, J. L. 1964. An experimental study of air flow in a corn plant air layer. Bull. Natl. Agric. Sci., A 11, 19-66.

Wyngaard, J. C. and Coté, O. R. 1971. The budget of turbulent kinetic energy and temperature variance in the atmospheric surface layer. J. Atmos. Sci., 28, 190-201.