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MEASUREMENT OF EDDY MOMENTUM FLUX NEAR THE GROUND

By

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Abstract

Field measurement of eddy transport of momentum over bare ground using the combination of a sonic anemometer and an analog data analyser was made. By this method of observation the amount of vertical eddy momentum flux can be obtained in real time. As a result of the experiment, it is now clear that the drag coefficient increases with decreasing wind speed in weak wind conditions by less than a few meters per second, and that the contribution of long period fluctuation longer than 100 sec in period to the total eddy momentum flux is not so large, but is about 10%.

1. Introduction

For the study of interactions between micro- and large-scale meteorological processes, it is fundamental to estimate precisely the magnitude of the vertical eddy transport of energy in the surface boundary layer. The eddy correlation method using a sonic anemometer-thermometer is the most promising technique for the measurement of eddy transport at present (Mitsuta [1968b]), because the sonic anemometer is the only reliable means of vertical velocity component measurement. Even if we have good sensors, there still remains a difficulty in applying this method in field experiments. This is in data processing because it is necessary to read and process huge amounts of data in order to ascertain eddy flux with sufficient accuracy (Mitsuta, Hanafusa and Sahashi [1967]). To overcome this difficulty and save time in data processing, an analog data analyser for eddy flux measurement has been developed by the present authors. With this instrument, mean values, standard deviations and cross covariances of meteorological entities can be obtained in real time.

In this paper the results of momentum flux measurement with the sonic anemometer and the analog data analyser over bare ground are presented.

2. Method of measurement

The measurement was made at the same experimental field where one of the authors had made observations of eddy momentum transport by a sonic anemometer for the first time, in which normal digital data processing was applied (Mitsuta [1968a]). The test field is open bare ground extending about 50 m upwind, while beyond that a flat sweet potato field extends for about 500 m. In order to discount the inhomogeneity of the surface the height of the measurement was restricted below a few meters from the ground as in the previous experiment.

The new type three dimensional sonic anemometer-thermometer with sound paths of 20 cm in length (Mitsuta, Miyake and Kobori [1967]) was used in this experiment. This was installed at a height of 1.5 m on the mast. The horizontal and vertical components of wind velocity are measured by this single instrument. The profile of wind speed as a reference was measured at the same time with five small 3-cup anemometers on the mast of 6 m in height.

The outputs of the sonic anemometer were directly analysed by the analog data analyser (Mitsuta and Hanafusa [1970]). The outputs of the analyser are the mean values and standard deviations of three components of wind velocity and covariances of vertical and two horizontal components. Each output is smoothed in value by low pass filters with time constants of 100 sec for means and covariances and 200 sec for standard deviations. They are sampled and printed out by a slow speed data logger every 60 seconds.

As the horizontal sound paths of the sonic anemometer cross at 120° to attain wide measuring angles, the total momentum flux is given by the following, using the coordinate transform formula given by Mitsuta [1968b].

$$M=-\frac{\sqrt{3}\,\rho}{2\sqrt{\bar{u}_1^2+\bar{u}_2^2+\bar{u}_1\bar{u}_2}}\{(2\bar{u}_1+\bar{u}_2)\overline{u_1'w'}+(\bar{u}_1+2\bar{u}_2)\overline{u_2'w'}\}, \tag{1}$$

where u_1 and u_2 are the two horizontal components and w the vertical component of wind velocity and ρ the density of air, and the bar above the symbol means the mean value over the total observation period.

At the same time the outputs of the analog data analyser are the mean values sampled every 60 seconds (denoted by a hat above) of $\hat{u}_1$, $\hat{u}_2$, $\hat{w}$, $\widehat{u_1w}$ and $\widehat{u_2w}$. Thus the values of covariances averaged over the total sampling duration are obtained as

$$\left.\begin{aligned}\overline{u_1'w'}&=\overline{\widehat{u_1w}}-\bar{\hat{u}}_1\times\bar{\hat{w}},\\ \overline{u_2'w'}&=\overline{\widehat{u_2w}}-\bar{\hat{u}}_2\times\bar{\hat{w}},\end{aligned}\right\} \tag{2}$$

and Eq. (1) becomes,

$$M=-\frac{\sqrt{3}\,\rho}{2\sqrt{\bar{\hat{u}}_1^2+\bar{\hat{u}}_2^2+\bar{\hat{u}}_1\bar{\hat{u}}_2}}\{(2\bar{\hat{u}}_1+\bar{\hat{u}}_2)(\overline{\widehat{u_1w}}-\bar{\hat{u}}_1\bar{\hat{w}})+(\bar{\hat{u}}_1+2\bar{\hat{u}}_2)(\overline{\widehat{u_2w}}-\bar{\hat{u}}_2\bar{\hat{w}})\}. \tag{3}$$

By this method the total value of the total covariance can be obtained without

Table 1. The results of the observation

Run No.	Date	Time	Wind direction	Wind speed (m/sec)					τ (dyne/cm^2)	σ_m (cm/sec)	u_* (cm/sec)	$C_d \times 10^{-2}$
				5.0 m	3.0 m	1.5 m	1.0 m	0.5 m				
4-1	Aug. 19, '69	09 : 58-10 : 42	E	3.45	3.05	2.80	2.40	1.95	0.40	52	18	0.42
4-2	〃	10 : 43-11 : 34	E	4.20	3.65	3.20	2.80	2.35	0.52	46	21	0.42
5	〃	11 : 36-12 : 30	S E	3.45	2.80	2.45	2.15	2.05	0.37	39	17	0.51
6	〃	13 : 00-13 : 35	E S E	2.70	2.35	2.15	1.70	1.60	0.69	37	24	1.2
7	〃	14 : 30-15 : 22	S S W	1.95	1.70	—	1.45	1.20	0.07	31	7	0.23*
9	〃	17 : 19-18 : 32	WNW	2.70	2.35	—	1.60	1.30	0.08	23	8	0.18*
10	〃	18 : 33-19 : 39	WNW	2.20	1.90	—	1.05	0.90	0.96	20	28	3.5*
11	Aug. 20, '69	10 : 37-11 : 59	SW	1.55	1.35	—	1.20	—	0.28	32	15	1.5*
12	〃	12 : 00-12 : 59	—	2.40	2.15	2.05	1.55	1.60	0.17	41	15	0.33
13	〃	13 : 34-14 : 10	—	5.20	4.70	4.10	3.65	3.00	1.06	53	30	0.52
14	〃	14 : 17-15 : 04	W	5.75	5.25	4.50	4.30	3.45	0.79	53	26	0.32
15	〃	15 : 58-16 : 56	WNW	4.45	4.05	3.60	3.15	2.65	2.78	46	48	1.8
16	〃	17 : 07-18 : 10	WNW	5.65	5.10	4.40	4.15	3.30	1.21	66	32	0.52
17	〃	18 : 11-19 : 06	W	3.70	3.30	2.85	2.40	2.05	0.28	35	15	0.28
18	〃	19 : 23-20 : 21	WNW	2.25	1.90	1.45	0.95	—	0.09	15	9	1.1
20	〃	22 : 43-23 : 38	—	—	—	—	—	—	0.06	2	7	—
24-1	Aug. 21, '69	06 : 49-07 : 33	—	—	—	—	—	—	0.06	11	7	—
24-2	〃	07 : 49-08 : 33	—	—	—	—	—	—	0.06	12	7	—
24-3	〃	08 : 34-09 : 27	—	—	—	—	—	—	0.03	17	5	—
25	〃	12 : 36-13 : 33	W	3.15	2.80	2.45	2.15	1.90	0.41	33	18	0.56
26	〃	13 : 48-14 : 32	W	2.70	2.50	2.35	1.80	1.75	1.82	28	39	2.7
27	〃	15 : 05-16 : 02	W	3.20	2.60	2.65	2.15	1.80	2.22	32	43	2.6
28	〃	16 : 03-17 : 00	W	3.45	3.15	2.85	2.40	2.10	0.35	34	17	0.36
29	〃	17 : 12-18 : 09	WNW	1.95	1.75	1.75	1.30	1.30	0.33	27	17	0.89
T-4	Aug. 23, '69	08 : 10-09 : 03	W	14.60	13.30	10.70	11.30	8.60	7.70	—	80	0.56
											mean value	0.98

* The wind speed at 1.5 m is interpolated from the values of wind speed at other levels.

filtering the low frequency component. This is the same process of analysis as the Evapotron (Dyer and Maher [1965]). The length of the total sampling duration should be about one hour or so.

3. The results of the measurement and discussions

The experiment was made during the period from 19th to 23rd Aug. 1969. The observed momentum fluxes and the related meteorological conditions are shown in Table 1. The last run was an observation in a typhoon wind, in which wind speed at the height of 1.5 m exceeded 10 m/sec.

An example of traces of the input and output of the analog data analyser in Run T-4 is shown in Fig. 1. The scales of horizontal components increase downward. The outputs of mean values are somewhat delayed as they are filtered by the low pass filters of 100 sec in time constant.

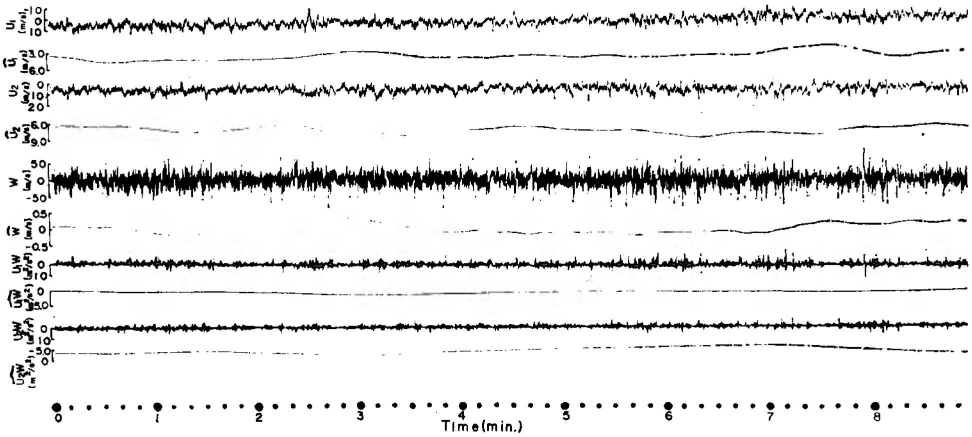

Fig. 1. The monitoring traces of input and output of the analog data analyser in Run T-4.

As is clear from this figure the smoothed curve of the vertical component (indicated as $\bar{w}$) fluctuates slowly with unexpectedly large amplitude which is as large as 0.5 m/sec. The existence of such large slow changing vertical motion at the very low level of 1.5 m above the ground has never been reported before. This might be evidence of the existence of a helical circulation as pointed out by Angell and Pack [1967]. Such slow changing vertical motion would be the cause of error in vertical wind component measurement, if the sampling duration is as short as the half period of the fluctuation. In such a case, a large mean vertical component will be observed, which will cause misunderstanding of the observed results. The r m s value of the low frequency component of the vertical velocity throughout Run T-4 (53 min), which is the output of the low pass filter sampled in every 60 sec, $\hat{w}$, is as large as 0.15 m/sec.

Even though there is such large slow changing vertical motion, its contribution to the total eddy momentum flux is relatively small. This is because the amount of covariance between the vertical and horizontal velocity components is filtered by low pass filters ($\hat{w}$ and $\hat{u}$) ; this is

$$\overline{(\hat{u}-\bar{\hat{u}})(\hat{w}-\bar{\hat{w}})}=0.064\ (\mathrm{m/sec})^2,$$

while the total covariance is 0.64 (m/sec)^2 as shown in Table 1. Therefore the contribution of the long period changes longer than 100 sec in period is only 10% of the total momentum flux. The mean value of the drag coefficients to 1.5 m wind speed is 0.98×10^{-2}. This value is almost the same as the value obtained on the same place (Mitsuta [1968a], Mitsuta, Hanafusa and Maitani [1970]), and would be the representative value for open bare ground.

However the deviation of each drag coefficient from the mean value seems to increase with decreasing wind speed, especially when wind speed less than 3 m/sec. The values of the drag coefficient are plotted against the mean wind speed at 1.5 m in Fig. 2. In this figure the results of the previous experiments at the same place are also shown (Mitsuta [1968a], Mitsuta, Hanafusa and Maitani [1970]).

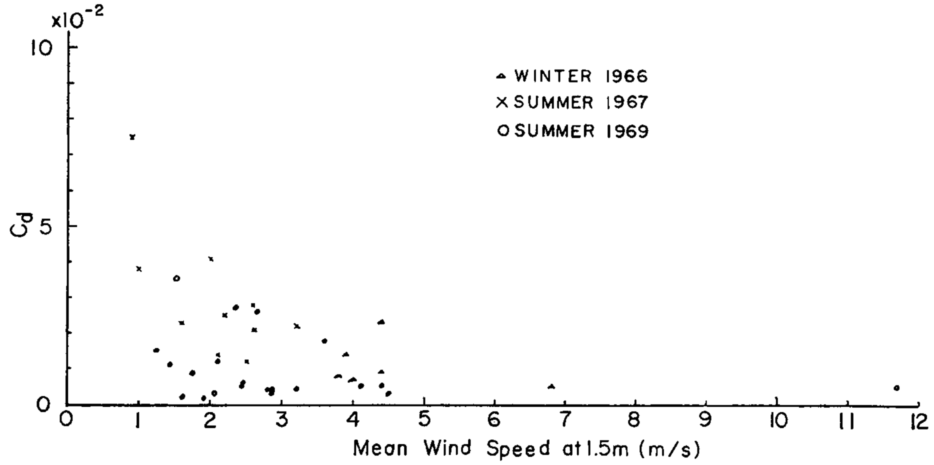

Fig. 2. The variation of the drag coefficient C_d with the mean wind speed {△: winter 1966 (Mitsuta [1968a]), ×: summer 1967 (Mitsuta *et al.* [1970]), ○: summer 1969}

The increase of drag coefficient with decreasing wind speed in the low wind speed range below 3 m/sec is clearly seen in this figure. The drag coefficient in 1 m/sec wind is more than five times as large as the average value in high winds above 3 m/sec, in which drag coefficient becomes constant. This increase of drag coefficient in low wind speed might correspond to the transition of airflow from turbulent to smooth, in which region the drag coefficient is a function of the Reynolds number. Detailed analysis of this subject will be published in near future.

4. Conclusions

Eddy momentum transport over open bare ground was observed by the use of the combination of a sonic anemometer and an analog data analyser. By the aid of the analog data analyser the values of the momentum transport can be obtained easily in real time, which is the great help in saving time for data processing and the resultant mean value of drag coefficient over bare ground to the mean wind speed at 1.5 m is about 1.0×10^{-2}.

As a result, it is now clear that there exists a quite large low frequency component in vertical wind velocity fluctuations. However such long period changes are not so important to the total momentum flux. The contribution of the fluctuation longer than about 2 minutes to the total momentum flux was only 10 % in one case.

At the same time, it is also clear that the drag coefficient increases with decreasing wind speed in low wind speed regions lower than 3 m/sec. Above that wind speed it is almost constant. This may indicate the existence of a transient region in flow from turbulent to smooth in the low wind speed region lower than 3 m/sec above the open bare ground.

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