TURBULENT FLUXES OVER THE LAKE KASUMIGAURA

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By

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Abstract

The results of the measurement of turbulent fluxes on Lake Kasumigaura as part of a project for the study of evaporation from reservoirs are presented in this paper. The sensor used in this study is the combination of the sonic anemometer and the fine psychrometer. The data are analysed by the analog data analyser. The turbulent fluxes of momentum, sensible and latent heat are obtained as well as the mean values, and standard deviations of meteorological parameters are also obtained. The mean ratio of the standard deviation of vertical velocity to the friction velocity is 1.1 and the mean drag coefficient is about 4×10^{-3}. The total evaporation from the lake on a fine day in December is about 0.6 mm. Fairly large downward water vapor flux is seen in the daytime and upward flux in the night time. The mean vertical motion is observed, and this might be caused by the bank, 4 meters high, behind. The difference between vertical turbulent flux and the cross stream line turbulent flux is discussed.

1. Introduction

Water loss from reservoirs by evaporation is an important and serious problem related to the effective usage of water resources in many countries. At the same time, evaporation from the water surface plays an important role in the energy transfer processes from the earth surface to the atmosphere. In spite of its importance, the process of evaporation or the water vapor flux above the water surface has not been well understood. A new research project for the study of evaporation from a wide body of water has started on an inter-university scale in Japan. As a part of this project, a joint experiment on evaporation from the Lake Kasumigaura, the second largest lake in Japan, was undertaken in December 1969.

This is the report of the results of turbulent transport process studies over water by the use of a sonic anemometer-thermometer and a fine thermocouple psychrometer made by the present authors in this experiment.

2. The method of observation

The most reliable method of turbulent vertical flux of meteorological entities is the eddy correlation method using a sonic anemometer as a vertical component sensor (Mitsuta [1968]). For the measurement of water vapor flux, a quick response psychrometer is the most practical sensor of humidity fluctuation. In this experiment the combination of the new three dimensional sonic anemometer-thermometer with sound paths of 20 cm (Mitsuta, Miyake and Kobori [1967]) and a fine theromocouple psychrometer of 0.12 mm wires (Sano and Mitsuta [1968]) was used as the sensor.

As the long term flux data are needed in this study of water loss from the lake, a newly developed analog data analyser, by which real time analysis of water vapor as well as momentum and sensible heat flux is possible (Mitsuta and Hanafusa [1970]), was employed for data processing to save time in data handling, which has hitherto been the great disadvantage in getting eddy flux data by the eddy correlation method. The derivation of water vapor flux was done by the use of the simplified method of computation proposed by one of the present authors (Hanafusa [1970]).

By the use of the analog data analyser, the mean values (the outputs of the low-pass filter with time constant of 100 sec), the r m s values (the filtered outputs with 200 sec low-pass filters of the r m s values of the signals filtered by high-pass filters of 100 sec in time constant) and the cross products of two signals filtered by the output low-pass filters with time constant of 100 sec can be obtained, which are scanned and printed out at intervals of one minute by a slow speed data logger.

In this experiment, bacause of the limitations of transportation of instruments the observed data were multiplexed on the data recorder (the system supplied by TEAC Co., AU-1000 S and R-200) at the field, and were brought back to the laboratory where they were played back and processed by the analog data analyser. The total system is shown in Fig. 1. The value with a hat is the value smoothed by a low-pass filter with time constant of 100 sec and sampled at intervals of one minute dy the data logger. The horizontal sound paths of the sonic anemometer cross at 120° and the two outputs of horizontal wind component u_1 and u_2 are not the orthogonal components. w, T_d and T_w are vertical velocity component, dry- and wet-bulb temperature respectively.

The observation is continued for about one hour for each run and the flux over this period can be derived from the mean values of the output of the printer, which are sampled at intervals of one minute, and is shown as follows

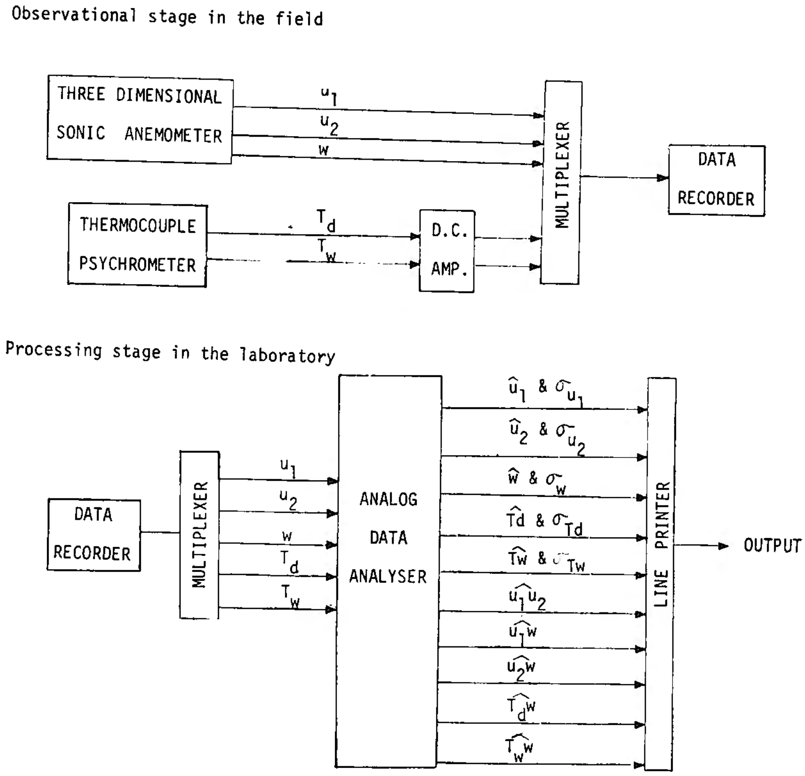

Fig. 1. The block diagram of the observation and analysis.

$$\tau = -\rho\overline{u'w'}$$

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

$$H = C_p\rho\overline{T_d'w'}$$

$$= C_p\rho(\overline{T_d\hat{w}}-\overline{\hat{T}_d}\,\overline{\hat{w}}), \quad (2)$$

$$E = \rho\overline{q'w'}$$

$$= A\rho\overline{T_w'w'} - B\rho\overline{T_d'w'} \quad (3)$$

$$= A\rho(\overline{T_w\hat{w}}-\overline{\hat{T}_w}\,\overline{\hat{w}}) - B\rho(\overline{T_d\hat{w}}-\overline{\hat{T}_d}\,\overline{\hat{w}}), \quad (4)$$

where the value with bar means the mean value over total sampling duration, for example one hour in length. Eq. (3) was given by Hanafusa [1970] and the parameters A and B are the function of the mean dry- and wet-blub temperature. As is clearly seen from these equations, the computations required for getting the magnitude of fluxes are only making the average of values of the output of the data logger printed out every minute over total sampling duration of one hour or so and calculating the Eqs. (1), (2) and (4).

As the averaging time is not so long, the output of the low-pass filter of the vertical component is not zero as pointed out in the case over land (Fujitani, Hanafusa and Mitsuta [1970]), but the averaged value of the output will tend to zero as the total sampling duration becomes long enough.

3. Field experiment and results

The first joint experiment was made on the southern part of Lake Kasumigaura as shown in Fig. 2, in December 1969. Because of technical difficulties, the observation mast could not be built in the water but was erected on the shore about 4 m from the coast line. The mast is 15 m high, and, on the top

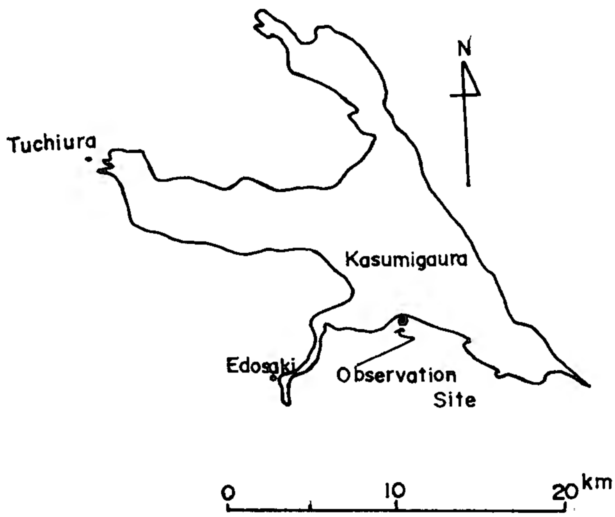

Fig. 2. Map of the observation site.

of this, it is expected that the characteristics of air flow over water can be measured as far as wind is from the lake, because the top level is enough high to be free from the effect of the internal boundary layer developing on the shore.

The instruments described previously are mounted on the top of the mast. Behind the mast, a bank 4 m in height runs parallel to the coast line.

The output signals were recorded in the instrumentation shack about 50 m from the mast. Observations were made only when the wind was from the lake.

The data were analysed later in the laboratory after the experiment as stated before. The results of the observations are summarized in Table 1. The profile measurement was also made by another research group and the

Table 1. Vertical turbulent fluxes and related parameters

Run No.	Date	Time of observation	Wind direction	Cloud cover	$\bar{u}$ (cm/s)	$\bar{w}$ (cm/s)	$w/\bar{u}$	T_d (°C)	T_w (°C)	q ($\times 10^{-2}$ g/g)	E (mW/cm²)	H (mW/cm²)	τ (dyne/cm²)	Friction velocity u_*(cm/s)	Drag coeff. C_d($\times 10^{-3}$) at 1.5m height	Stand. devia. of verti. comp. σ_w (cm/s)
K- 3	11th Dec. '69	21:01–21:37	N	0/10	536	67	0.13	6.6	4.7	0.45	6.1	0.4	1.36	33	5.90	17
K- 4	11th Dec. '69	22:27–23:21	NNE	0/10	622	30	0.05	6.4	4.3	0.43	9.7	−0.6	0.67	23	2.05	19
K- 5	12th Dec. '69	00:33–01:27	N	2/10	566	62	0.11	6.9	4.2	0.40	2.9	−2.4	0.57	21	1.62	22
K- 6	12th Dec. '69	02:36–03:30	NNW	1/10	279	30	0.11	6.5	4.4	0.44	−1.9	−0.8	0.18	12	—	20
K- 7	13th Dec. '69	10:56–11:21	ENE	3/10	536	11	0.02	7.7	4.3	0.38	0.7	5.0	0.89	27	5.17	24
K- 8	13th Dec. '69	11:36–12:29	NW	1/10	1020	97	0.10	9.1	4.2	0.31	1.3	−2.8	1.51	35	2.04	56
K- 9	13th Dec. '69	14:04–14:27	NW	1/10	1178	118	0.10	9.2	6.0	0.45	−7.9	3.0	1.01	29	1.05	57
K-10	13th Dec. '69	16:04–16:48	NW	1/10	827	87	0.11	6.6	5.6	0.53	−6.9	3.7	1.88	39	3.68	—
K-11	13th Dec. '69	21:38–22:07	NE	0/10	(570)	43	0.07	3.0	2.2	0.41	7.7	1.0	—	—	—	—
K-12	14th Dec. '69	00:43–01:23	N	0/10	284	40	0.14	—	—	—	4.1	−0.1	0.45	19	6.87	—
K-13	14th Dec. '69	06:37–07:10	NNW	0/10	325	36	0.11	1.6	1.0	0.38	4.0	2.4	0.59	22	4.91	—
K-14	14th Dec. '69	09:22–10:15	N	0/10	232	34	0.15	4.1	0.2	0.23	3.6	2.8	0.43	18	7.06	24

full results were not available at the time of the preparation of this paper. The results shown in this table are values observed by the sonic anemometer and the fine wire thermocouple psychrometer except the values of the drag coefficients, which were computed from the mean wind speed at 1.5 m over water with a small cup anemometer on the low mast.

The vertical component sensor of the sonic anemometer was installed vertically within errors of 0.5 degrees. However, as is clear from this table, large averaged values of vertical component were observed. This shows that the air flow was distorted by the bank in the lee side as discussed in the next section. In spite of the existence of vertical motion, the magnitude shown in this table is the value computed after the traditional definition of vertical eddy transport as shown in Eqs. (1), (2) and (4). The advection in the vertical direction is not taken account.

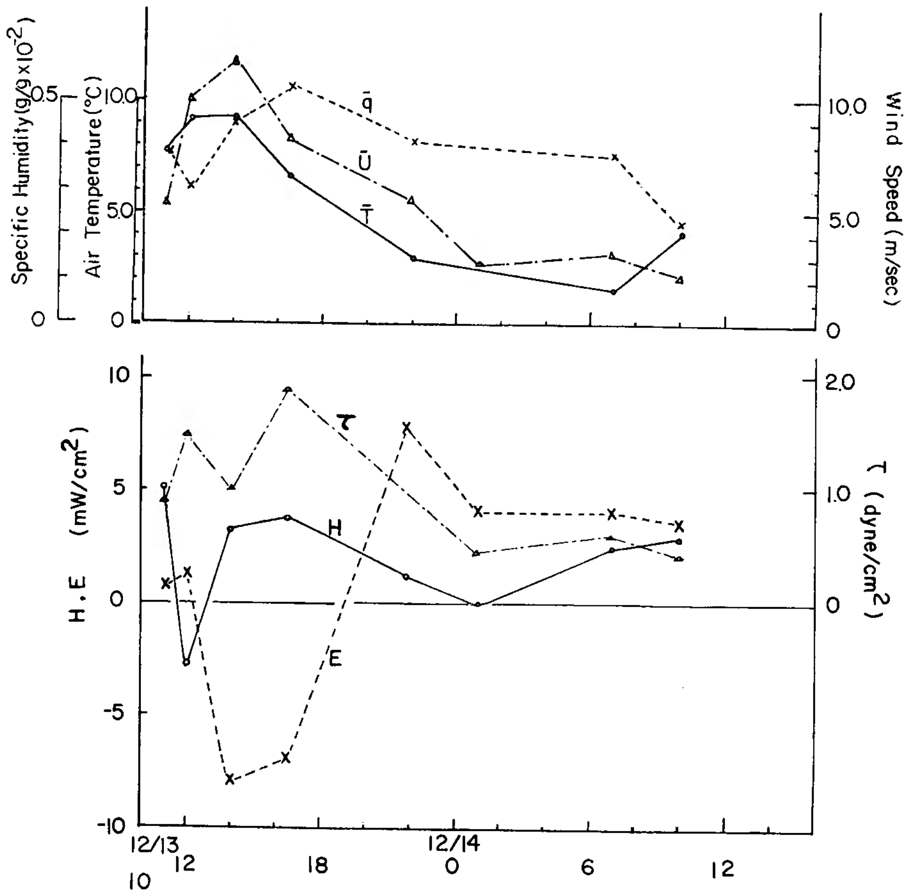

Fig. 3. An example of the time variations of vertical turbulent fluxes and mean quantities.

The mean ratio of the standard deviation of vertical velocity to the friction velocity is 1.1, which is compatible with the value obtained in a wind tunnel as shown by Lumley and Panofsky [1964].

The time changes of the mean values and turbulent fluxes from the morning of 13 th to the morning of 14 th are shown in Fig. 3. In the afternoon of 13 th large downward flux of water vapor or latent heat was observed but reason can not be seen merely from these data of the observation at one height. Quite large water vapor flux can be seen at night when momentum and sensible heat flux decrease.

The total evaporation in this study is estimated by integrating this curve to be about 0.6 mm in all. The mean drag coefficient is about 4×10^{-3}. This value is a little larger compared with the value observed over sea, but this may be the representative value over inland water.

These results will be discussed after the full results of the profile, surface temperature and other quantities observed by the other university groups are available.

4. Discussion

As is pointed out before, the significant amount of mean vertical motion was observed during the observation, when wind is from the lake. The ratio of mean vertical velocity to horizontal wind speed is almost one tenth, which shows that the stream line is not horizontal but inclining with an inclination of about 6 degrees or so. This inclination seems independent of wind speed but is dependent on wind direction. This may be caused by the existence of the bank behind the mast. The cross section from north to south which is the perpen-

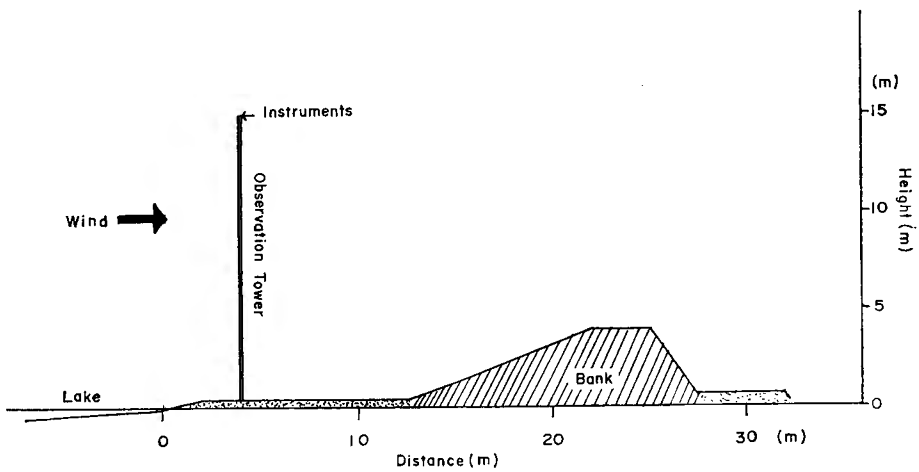

Fig. 4. Cross section of the topography near the observation site.

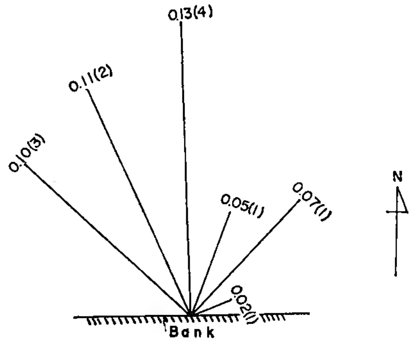

Fig. 5. Dependence of the ratio of the mean vertical velocity to the horizontal on wind direction.

dicular to the coast line is shown in Fig. 4. And the inclination of the stream line is shown as the function of wind direction in Fig. 5, from which the dependency of inclination on the wind direction is clearly seen. When wind is from north or perpendicular to the bank, the inclination angle is about 7 degrees. This is an interesting result, bearing the characteristics of air flow over a barrier.

However the definition of the vertical eddy transport in such inclining flow is the subject of reconsideration. The eddy transport to the direction perpendicular to the stream line is one alternate choice of the definition. The eddy flux of momentum to the perpendicular to the stream line can be defined, by the use of the result of error estimation of vertical flux with inclining vertical sensor (for example, Pond [1968]), as follows

$$-\rho\overline{u_s'w_s'} = -\rho\overline{u'w'}\cos 2\theta + \frac{1}{2}\rho(\overline{u'^2} - \overline{w'^2})\sin 2\theta \tag{5}$$

where θ is the inclination of the stream line and the suffix s means the velocity component parallel and perpendicular to the stream line. The values of terms in right hand side part can be estimated from the output of analog data analyser. The value of each term is shown in Table 2. The covariances to the coordinate frame relative to the stream line are larger than the values to the true vertical frame. The differences are about 30 to 60 % as seen in

Table 2. Comparisons of momentum fluxes relative to vertical and parallel to the stream line coordinate

Run No.	$\bar{u}$ (cm/s)	θ	$\overline{u'^2}$ (cm/s)^2	$\overline{w'^2}$ (cm/s)^2	$-\overline{u'w'}$ (cm/s)^2	$-\overline{u_s'w_s'}$ (cm/s)^2	$(\overline{u_s'w_s'}-\overline{u'w'})/\overline{u'w'}$
K- 4	622	3.0	4624	361	535	759	0.42
K- 7	536	1.0	13689	576	708	944	0.33
K-14	232	8.5	2025	576	342	539	0.62

the table. It is difficult to decide which value is more significant. However as the inclination decreases with height, the flux perpendicular to the stream line is difficult to define and contribution to the higher level can be defined easily by the flux by the traditional definition relative to the true vertical. Thus the fluxes in this definition are presented in this paper.

The mean value of the drag coefficients is presented in the preceding section but it is seen from Table 1 that the value varies with wind speed. The variation of drag coefficient with wind speed is shown in Fig. 6. The wind speed shown

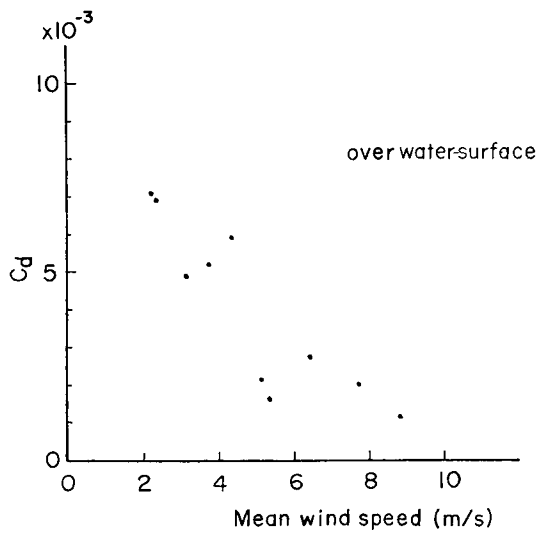

Fig. 6. Dependence of the drag coefficient C_d on mean wind speed at 1.5 m.

in this figure is the value at 1.5 m in height measured by the small cup anemometer which was used in computing drag coefficient. The drag coefficient increases with decreasing wind speed. This tendency is also seen over land as reported in another paper (Fujitani, Hanafusa and Mitsuta [1970]). This tendency agrees with the statement by Deacon *et al.* [1956] that the drag coefficient approaches to the value appropriate to the aerodynamically smooth flow below 5 m/sec at the height of 10 m over sea. This will be discussed in a separate paper.

This experiment will be repeated in near future and the detailed studies of eddy transport over the lake will be made after that.

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