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# ESTIMATION OF EVAPORATION RATE BY USE OF A SONIC ANEMOMETER

By

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**Abstract**

The evaporation rates from the water and soil surfaces are estimated by the eddy-correlation method which is, in principle, the most reasonable one, using a sonic anemometer and a fine thermocouple psychrometer. Cospectral analysis shows that the method seems to be applicable to the estimation of evaporation rate, in spite of rather long averaging time of 1 sec and short sampling duration of 5 min, taken here. The results are compared with those by the aerodynamic method, the heat-balance method and the pan method. It is found that there is a fairly good agreement between the results by the eddy-correlation method and those by Thornthwaite-Holzman's formula.

## 1. Introduction

Evaporation is an important part of the hydrological cycle of the water over the earth, and is expressed as a term of the turbulent vertical transfer processes in the air layer near the earth's surface. This phenomenon has been, therefore, received very much interests from many meteorologists and the scientists in other related disciplines (e.g., Sutton [1934] and Jeffreys [1919]). It has been required to establish a reliable method of estimating the evaporation or evapotranspiration rate from a surface of wide area, from the viewpoint of utility of water resources and other practical purposes (Robertson [1955]). The methods used usually in meteorology may be classified into the following five categories: pan method, atmospheric water-balance method, aerodynamic method, heat-balance method and eddy-correlation method.

Pan method is widely adopted for practical purposes. It is, however, well-known that there are some differences between evaporation rates from the pan and from the environmental wide surface. It is difficult to obtain the definite value of the correction factor or *pan coefficient* (Deacon, *et al.* [1958]). In the atmospheric water-balance method, the evaporation rate is given as the difference of inflow and outflow of the water vapour in the specified space, which has an evaporating surface as its lower boundary. This method requires troublesome observations, and it can give a comprehensive result only in special cases of a fairly wide area (Manabe [1957]).

In aerodynamic method, many authors have attempted to formulate the evaporation rate in term of the mean vertical profiles of humidity, temperature and wind speed. They have a basis upon aerodynamic consideration about the vertical eddy transfer process of water vapour. Typical examples of these formulae are proposed by Thornthwaite and Holzman [1939] and Montgomery [1940]. Verification of these formulae is not yet sufficiently made for all the possible meteorological conditions (Sahashi [1962]). Heat-balance method is based upon the idea that the latent heat of vaporization lost from the surface gives a measure of evaporated water mass. Since the evaporation rate calculated in this method is obtained as the residue of other transfer components such as eddy transfer of sensible heat and the radiative heat transfer and so on, there is a risk that all the errors contained in the estimation of the other components may be reduced to the results. Both methods, aerodynamic and heat-balance, contain, in general, doubtful assumption that the eddy transfer coefficient for momentum is equal to that for vapour or that the ratio of the eddy coefficient for sensible heat to that for latent heat is unity in all the meteorological conditions.

Eddy-correlation method does not contain such assumption, and is generally accepted as the most reasonable way to estimate the vertical eddy flux. The principle of this method is that the evaporation rate is proportional to the time mean of instantaneous product of eddy component of vertical velocity and excess of vapor content in the air layer near the surface. This method had been taken up by the present author [1962] in the case of the Miura Reservoir. At that time, measurement of the vertical velocity was made with hot-wire technique. The sonic anemometer was not developed yet in Japan. In practical use of the hot-wire technique, some difficulties must be overcome. Some uncertainties occur frequently in its calibration and careful handling is needed owing to its delicate structure.

Recently the staff members in Kyoto University have developed a sonic anemometer feasible in field observation (Mitsuta and Mizuma [1964] and Mitsuta [1966]). This instrument may be probably the most promising one without shortcomings such as that of the hot-wire technique. Development of this instrument makes us to attempt further examination of the eddy-correlation method. Actual observations were carried out above the water surface and soil surface, with comparative examination of other methods.

## 2. Instrumentation

The eddy-correlation method requires observing simultaneously the fluctuations of the vertical component of velocity and the vapour concentration. A sonic anemometer is used for the former, and a fine thermocouple psychrometer for the latter. For aerodynamic method, 3-cup Robinson type anemometers, aspiration psychrometers and the surface thermometer are used. A ventilated net-radiometer, aspiration psychrometer and thermistor thermometer are employed for heat-balance method. Brief descriptions of these equipments will be given in the following.

*Sonic anemometer.* Two of the sonic anemometers developed by the staff of Kyoto University (Mitsuta and Mizuma [1964] and Mitsuta [1966]) are employed. The sound path length is 0.6 m for *F-PT-1* type and 0.5 m for *PTD-5011* type, respectively. In *F-PT-1* type anemometer, the wind velocity is given as sweep length of a spot on an oscilloscope and recorded by a camera. *PTD-5011* sonic anemometer has a voltage analog output, and recorded by a pen oscillograph. These anemometers are mounted so that the sound path is vertical.

An examination must be made about the accuracy of moisture flux which will be obtained by these anemometers. The principle of this equipment is based upon the measurement of the apparent velocity of sound wave over a given path length, and the velocity is a function of the air temperature and the vapour concentration as well as the wind velocity component along the sound path. Vertical flux of water vapour determined by the eddy-correlation method is defined:

$$E(EC)=\overline{\rho w' q'}, \qquad \cdots\cdots\cdots\cdots(1)$$

where $w'$ is the vertical wind component, $q'$ is the fluctuation of specific humidity and the bar signifies the time mean. The observed value of vertical eddy velocity with a sonic anemometer $w'_{obs}$ is given by the following equation after Suomi, *et al.* [1959]:

$$w'_{obs}=w'-2\frac{c'}{\bar{c}}(w'+\overline{w'}), \qquad \cdots\cdots\cdots\cdots(2)$$

$$\frac{c'}{\bar{c}}\doteqdot\frac{T'_{sv}}{2\overline{T}_{sv}}, \qquad \cdots\cdots\cdots\cdots(3)$$

where $c$ is the velocity of sound, $T_{sv}$ is the sound virtual temperature defined as follows:

$$T_{sv}=T\left(1+0.32\frac{e}{p}\right).$$

Here, $T$ is the absolute air temperatue, $e$ is the vapour pressure along the sound path, $P$ is the atmospheric pressure and the prime means the departures from the mean value. Since it is plausible to assume that $\overline{w'}$ vanishes, Eq. (2) becomes

$$w'_{obs}=w'\left(1-2\frac{c'}{\bar{c}}\right). \qquad \cdots\cdots\cdots\cdots(4)$$

If the value of $q'$ is correctly measured, the following is obtained:

$$E(EC)=\overline{\rho w'\left(1-2\frac{c'}{\bar{c}}\right)q'}$$

$$\doteqdot\overline{\rho w'q'}-\overline{\rho w'q'\frac{T'_{sv}}{\bar{T}_{sv}}}, \qquad \cdots\cdots\cdots\cdots(5)$$

using Eqs. (1) and (4). The second term of the right-hand side is a correction term. It is, in general, supposed that there are some correlation among $w'$, $q'$ and $T'_{sv}$, and this term may not vanish. The value of $T'_{sv}/\bar{T}_{sv}$ is, however, usually the order of magnitude of $10^{-2}$, and the second term may be neglected within the error of several percents. These considerations permit us not to take into accout of the second term in our calculation of evaporation rates.

The frequency response of this sonic anemometer is discussed by Mitsuta [1966]. He treats the case of the sound path parallel to the mean wind direction. Although the sound path is vertical in our observation, his results may be applicable to our case, if non-isotropic characters of the eddy may not be so strong. Mean wind speed in our case is from 1.5 to 3.0 m/sec. Mitsuta's results show that our anemometer will measure only the wind fluctuation of frequency lower than 0.5 or 1.5 cps, under the limit of 90% gain.

*Fine thermocouple psychrometer.* For the fluctuation measurement of humidity, copper-constantan thermocouples of 0.04 mm diameter are employed as a psychrometer. Since Sheppard-Elnesr circuit (Sheppard and Elnesr [1957]) for the direct measurement of vapour pressure fluctuation has some problem about its accuracy, we decided to use a system of simple psychrometry. A wet-bulb wick is made of shredded gauze. Output of these thermocouples are connected with an electromagnetic oscillograph which has galvanometers of free period of 0.7 sec for the observation over the water and of 1/15 sec for that over the soil. As shown elsewhere by the present author (Sahashi [1968]), the time constant of dry-bulb thermometer is a function of wind speed, and that of wet-bulb one is a function of the wet-bulb temperature as well as the wind speed. In our observation, the mean wind speed is ca. 1.5 m/sec over the water and is ca. 2.0 m/sec over the soil, and the wet-bulb temperature is ca. 20°C for the former and ca. 0°C for the latter. The examination of frequency response of temperature measuring system including the galvanometer in our observation shows that 90% response will be obtained in the frequency range lower than 0.25 cps. It must be remembered at the analysis of these data.

No radiation shield or ventilation device is applied, because these are essentially improper in fluctuation measurement. For the effect of the insolation on a fine wire resistance thermometer, Kawamura [1947] could not find any definite difference in the output from the two resistance thermometers of 0.06 mm diameter, the one is shielded and the other is not. About the effect of ventilation on a wet-bulb thermocouple thermometer, Seo [1957] reported that there are no appreciable change in the psychrometric constant for a psychrometer of fine thermocouple, if the ventilation is more than about 10 cm/sec.

*Cup anemometer.* Three or four small and light 3-cup anemometers are employed for obtaining the vertical profile of mean wind and the number of the cup rotations is recorded by a pulse counter.

*Aspiration psychrometer.* Three aspiration psychrometers of thermistor thermometer which have ventilating fans driven by 100V A.C. are used for obtaining the vertical profile of mean temperature and humidity. Records of them are obtained by an electronic recorder.

*Pan evaporimeter.* Automatic floating evaporation pan constructed by Mitsuta [1964] is used. This evaporimeter has a floating pan of 1000 $cm^2$ evaporation area. Constant volume of water (ca. 18 liters) is supplied into the pan, and the water is drained into the water gauge after the prescribed time interval. After this process is finished, the constant water mass is again supplied into the pan. The water level in the gauge is taken out as D.C. voltage and lead to an electronic recorder. These processes are carried out automatically.

*Surface thermometer.* A thermistor thermometer with simple float and radiation shield is set at the water surface. The thermometer forms one arm of a Wheatstone bridge circuit, and the unbalanced current is recorded by an electronic recorder.

*Water temperature thermometer.* Thermistor thermometers are mounted at the depth of 10, 30 and 70 cm below the water surface. Recording system is the same as that of the surface thermometer.

*Ventilated net-radiometer.* Ventilated net-radiometer is mounted at the height of 1.0 m above the water surface and the output is recorded by an electronic recorder.

## 3. Observation and reduction of the data

*The site and installation.* Observation over the water surface is carried out at the rectangular pond which has the size of about 80 m×120 m. All the sensing elements are mounted above a fixed raft of 3 m square near the center of the pond, and they are connected with the recorders set on the land by cables. Observation over soil surface is carried out at the center of the area of about 60 m×150 m. All recorders are set in a hut which stands 40 m distant from the observation site. The installations are given in Figs. 1(a) and 1(b), and Table 1. Installing level of the sonic anemometer and the thermocouple thermometers

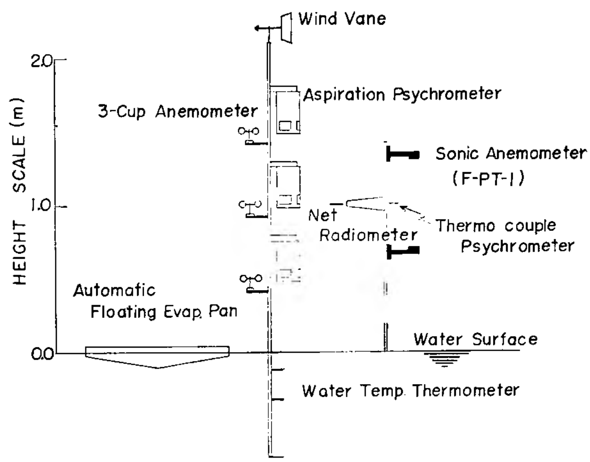


Fig. 1(a). Schematic diagram of installation of instruments. Over the water surface observation.

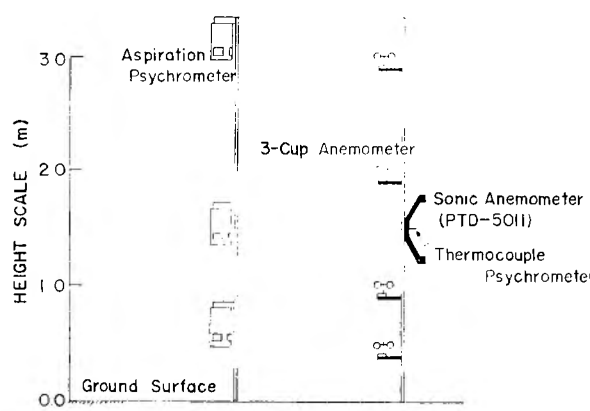


Fig. 1(b). Schematic diagram of installation of instruments. Over the soil surface observation.

Table 1. Installation level of sensors

| Sensor | Over water surface (m) | Over soil surface (m) |
|---|---|---|
| Sonic anemometer | 1.0 | 1.5 |
| Thermocouple psychrometer | 1.0 | 1.5 |
| Cup anemometer | 1.5 | 3.0 |
| | 1.0 | 2.0 |
| | 0.5 | 1.0 |
| | | 0.5 |
| Aspiration psychrometer | 1.5 | 3.0 |
| | 1.0 | 1.5 |
| | 0.5 | 0.5 |
| Net radiometer | 1.0 | — |
| Water temperature thermometer | 0.0 | — |
| | 0.1 | — |
| | 0.3 | — |
| | 0.7 | — |

for measuring the flux over a limited area is limited in two ways. The lower limit of the level might be given by consideration of the minimum size of eddy effective to the transfer process in question, and the measurable minimum eddy size is determind by the response of the sensor. The upper limit of the level might be given by the thickness of the boundary layer produced by the surface in question here. For the former consideration, the figure presented by Deacon [1959] is useful. This shows that 80% flux will be given at the height of 75 cm under unstable condition and 1.5 m under stable one, taking account of the wind speed nearly equal to or higher than 1.5 m/sec and of frequency response of more sluggish instrument or the thermocouple thermometer. For the thickness of the boundary layer, there is no definite information. However, it may be accepted that the thickness may be the order of magnitude of 1/100 of the distance from the leading edge of the surface in question. This gives the order of magnitude of 1 m, in our case. The installing levels adopted here are given in Table 1.

The observations are carried out in September and October 1964 over the water surface, and in January 1965 over the soil surface. In the former observation, it is attempted to compare the evaporation rate estimated by the eddy-correlation method with those by Thorthwaite-Holzman's formula, Montgomery's formula, heat-balance method and the pan method. Over the soil surface, comparative measurements by the eddy-correlation method and the Thorthwaite-Holzman's formula are made.

The observing time interval is restricted mainly by the recording equipment and is 5 min in the both cases, except for the pan method. The floating pan

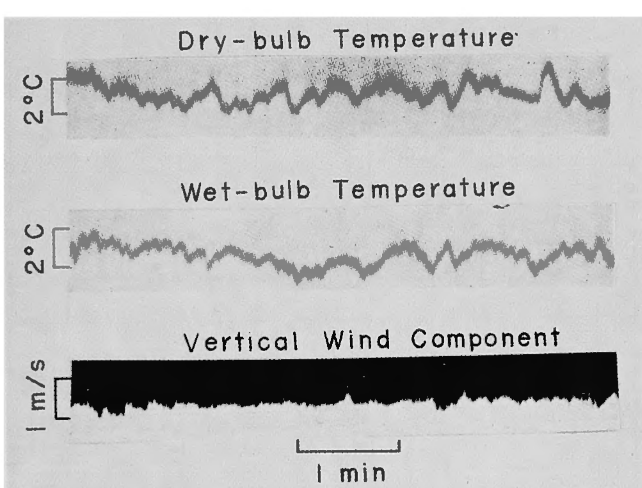


Fig. 2. Example of fluctuation record. From over the water surface observation. Time advance from left to right.

Table 2(a). Observed values and related quantities over water surface

| Run No. | Data | Time | Weather Cloud | Wind Speed (cm/sec) | | Air Temperature (°C) | | | Vapour pressure (mb) | | | Water Temperature (°C) | | | Richardson Number |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $U_{50}$[1] | $U_{150}$[1] | $\theta_s$[2] | $\theta_{50}$[1] | $\theta_{150}$[1] | $e_s$[2] | $e_{50}$[1] | $e_{150}$[1] | $\theta_{10}$[1] | $\theta_{70}$[1] | $\theta_{150}$[1] | Ri, 100[1] |
| | | h m | | | | | | | | | | | | | |
| F-1 | '64 Sept. 8 | 12 55 | ○ 0 | 85 | 114 | 31.9 | 29.9 | 29.2 | 47.28 | 19.33 | 17.41 | 30.4 | 27.9 | 27.7 | −0.27 |
| F-2 | 〃 | 13 10 | ○ 0 | 74 | 110 | 33.0 | 30.1 | 29.4 | 50.31 | 19.31 | 17.49 | 30.9 | 27.9 | 〃 | −0.17 |
| F-3 | 〃 | 13 25 | ○ 0+Cu | 93 | 114 | 33.5 | 30.5 | 29.7 | 51.74 | 18.93 | 17.28 | 31.3 | 28.1 | 〃 | −0.59 |
| F-4 | 〃 | 13 40 | ○ 0+Cu | 138 | 174 | 33.5 | 30.7 | 29.8 | 51.74 | 18.35 | 17.22 | 32.0 | 28.2 | 〃 | −0.22 |
| F-5 | 〃 | 13 55 | ○ 0+Cu | 112 | 128 | 32.8 | 31.0 | 30.2 | 49.75 | 17.50 | 16.52 | 31.4 | 28.0 | 〃 | −1.00 |
| F-6 | 〃 | 14 10 | ○ 0 | 120 | 174 | 33.0 | 30.9 | 30.1 | 50.31 | 17.13 | 15.38 | 31.3 | 28.0 | 〃 | −0.09 |
| F-7 | 〃 | 14 25 | ○ 0 | 131 | 194 | 33.0 | 31.3 | 30.6 | 50.31 | 17.73 | 16.68 | 31.3 | 28.2 | 27.8 | −0.06 |
| F-8 | 〃 | 14 40 | ○ 0 | 108 | 138 | 32.9 | 31.4 | 30.7 | 50.03 | 17.45 | 18.61 | 31.5 | 28.0 | 〃 | −0.25 |
| F-9 | 〃 | 14 55 | ○ 0 | 146 | 189 | 32.9 | 31.4 | 30.8 | 50.03 | 17.88 | 16.55 | 31.7 | 28.2 | 〃 | −0.10 |
| F-12 | 〃 | 15 40 | ○ 0 | 129 | 160 | 32.7 | 31.4 | 30.8 | 49.47 | 18.32 | 17.76 | 31.4 | 28.4 | 〃 | −0.20 |
| F-13 | '64 Sept. 29 | 14 10 | ⦶ | 144 | 236 | 30.7 | 24.7 | 24.2 | 44.17 | 24.15 | 23.36 | | | | 0.00 |
| F-14 | 〃 | 14 19 | ⦶ | 144 | 236 | 29.8 | 24.5 | 24.4 | 41.95 | 24.06 | 23.23 | | | | 0.00 |
| F-15 | 〃 | 14 45 | ⦶ | 170 | 270 | 27.8 | 24.4 | 24.3 | 37.36 | 23.68 | 23.59 | | | | 0.00 |
| F-16 | 〃 | 14 55 | ⦶ | 170 | 270 | 27.3 | 24.3 | 24.2 | 36.28 | 23.52 | 23.28 | | | | 0.00 |
| F-17 | '64 Oct. 16 | 11 31 | ○ 0 | 140 | 148 | 22.8 | 24.6 | 24.3 | 27.75 | 26.07 | 26.27 | | | | −1.23 |
| F-18 | 〃 | 11 42 | ○ 0 | 144 | 220 | 23.0 | 25.0 | 24.6 | 28.09 | 26.28 | 26.92 | | | | −0.39 |

1) Suffix shows measured height or depth in cm.

2) Suffix shows temperature and vapour pressure at the surface.

evaporimeter can measure the evaporation rate for 3 hours. An example of the fluctuation records is shown in Fig. 2.

*Reduction of the data.* Before analysis of the fluctuation records, "averaging time" and "sampling duration" should be determined. The former is, of course, denpendent upon the response of the sensors employed, and the latter upon the observing time interval. Many authors dealing with these problems have determined such time in rather convenient way, and proposed the value from 0.5 sec to 2.0 sec as averaging time (Swinbank [1951] and Deacon [1959]), and the value from 1 min to 5 min as samplingduration (Swinbank [1955], Deacon [1955] and Shiotani [1955]). The discussions given in the previous section show that the sonic anemometer can measure the wind fluctuation of frequency lower than 0.5 cps to 1.5 cps and can measure the wet-bulb temperature of frequency lower than 0.25 cps under the limit of 90% gain, respectively. The averaging time of 1 sec is adopted in our cases.

Reading the $w'$ record in every 0.25 sec, the mean of the successive four values is taken as 1 sec-mean. The temperature records are read out in every 0.5 sec, and the mean of successive two values is taken as 1 sec-mean. From the values of dry- and wet-bulb temperature at every 1 sec, the specific humidity $q'$ is calculated by the convenient meteorological table.

The sampling duration is given by the observing time interval of 5 min, considering that it is not so short compared with the other author's interval. The other reference data such as the mean wind speed, the mean air temperature and so on are read out as 5 min mean. These data are listed up in Table 2, as well as the weather conditions and the vertical stability.

Table 2(b). Observed values and related quantities over bare soil surface

| Run No. | Date | Time | Weather Cloud | Wind Speed (cm/sec) | | | | Temperature (°C) | | | Vapour Pressure (mb) | | | Richardson Number |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $U_{50}$[1] | $U_{100}$[1] | $U_{200}$[1] | $U_{300}$[1] | $\theta_{50}$[1] | $\theta_{150}$[1] | $\theta_{300}$[1] | $e_{50}$[1] | $e_{150}$[1] | $e_{300}$[1] | $Ri_{175}$[1] |
| | | h m | | | | | | | | | | | | |
| U-11 | '65 Jan. 13 | 14 31 | ◎ 7Ac | 180 | 200 | 232 | 270 | 6.0 | 5.9 | 5.9 | 4.72 | 5.02 | 5.63 | −0.01 |
| U-12 | 〃 | 14 45 | ◎ 7Ac | 154 | 159 | 180 | 226 | 5.7 | 5.5 | 5.5 | 4.81 | 5.06 | 5.65 | −0.06 |
| U-13 | '65 Jan. 15 | 12 17 | ◎ 7Ac | 158 | 197 | 255 | 270 | 8.6 | 8.4 | 7.9 | 5.53 | 5.66 | 6.64 | −0.29 |
| U-14 | 〃 | 13 43 | ◎ 3Ac | 233 | 256 | 311 | 350 | 7.5 | 7.5 | 7.3 | 5.90 | 6.01 | 6.66 | −0.09 |

[1] Suffix shows the measured height in cm.

## 4. Discussions on the results

It is necessary to examine whether or not the values of eddy vertical transport of water vapour obtained by the procedures mentioned above will remarkably be influenced by the values of the averaging time and the sampling duration adopted here. The present author attempts to treat this problem through some spectral analysis, before the discussion of the estimated results of evaporation rate itself.

Treating the fluctuations of the 1 sec-values of the vapour pressure, $e'$, and of the vertical velocity, $w'$, their spectral densities are obtained. The computations are carried out with the digital computer *OKITAC-5090H* in the Research Reactor Laboratory, Kyoto University. The computing program is made by Mizuma [1967]. Some examples of the spectra of $e'$ are shown in Fig. 3. In this figure and the several following ones, the letter F is refferred to the over-water observation, and the letter U to the over-soil observation. It is found that the distribution of the spectral density of $e'$ in the frequency range from 0.01 to 0.2 cps almost coincides with the minus five-third law, in spite of rather lower observing height; that is, 1.0 m for the run F-1 and F-3, and 1.5 m for the run U-13 and U-14. Observing the fluctuation of absolute humidity at the height of 3.5 m above the ground, Elagina [1963] shows that the distribution of spectra coincides with the minus five-third law in the frequency range from 0.01 to 1.5 cps. The results of the present author verifies Elagina's suggestion that the law may hold at least for the humidity fluctuation of higher frequency than 0.01 cps even in the air layer of height 1 m or so above the surface. The spectral density of $w'$ shown in Fig. 4 coincides with the minus five-third law only in the frequency range from 0.1 to 0.3 cps, and in the lower frequency range there are

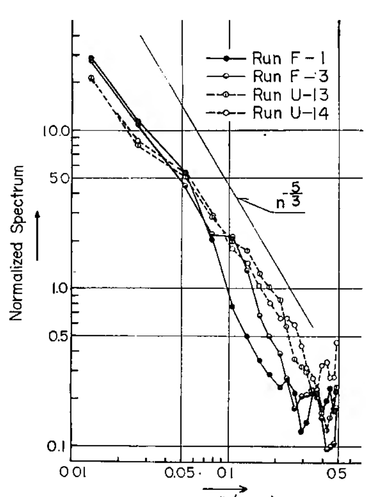


Fig. 3. Spectral density distribution of vapour pressure fluctuation, normalized by the total variance.

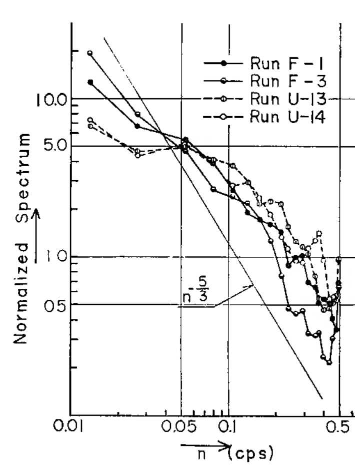


Fig. 4. Spectral density distribution of vertical component of eddy velocity, normalized by the total variance.

some departure from the law. This may suggest that the structure of wind field in the lower frequency is somewhat different from that of the vapour pressure. It may be interesting that the distribution of spectra of temperature fluctuations for the same runs obtained by Hanafusa [1965] almost coincides with that of $e'$ rather than that of $w'$, as shown in Fig. 5.

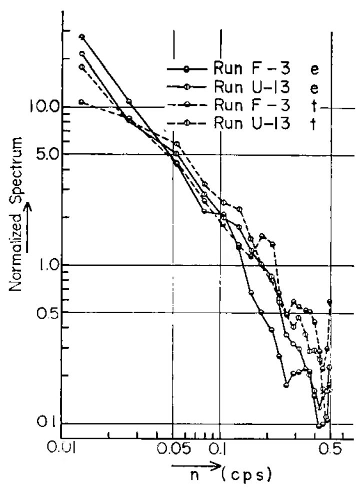


Fig. 5. Comparison between spectral density distribution of vapour pressure fluctuation and that of temperature fluctuation.

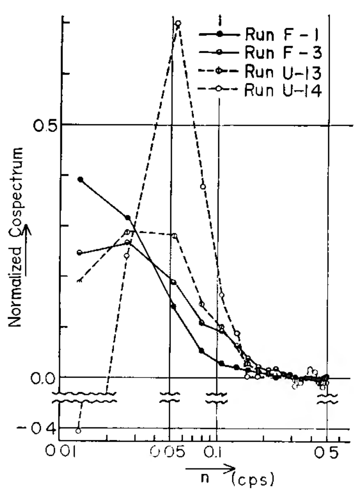


Fig. 6. Distribution of cspectrum of $w'$ and $e'$, normalized by the total covariance.

In the estimation of evaporation rate by the eddy-correlation method or by Eq. (1), $w'$ and $q'$ should observed in the whole range of frequency effective to the vapour flux. Unless the observations cover the range, the calculated results may be under-estimated. The contribution of various frequencies to the vapour flux is inspected by the cospectrum of $w'$ and $e'$, and some examples are given in Fig. 6. Somewhat remarkable peak of the cospectrum can be found near the frequency of 0.03 cps. This fact implies that the fluctuations of very high and very low frequencies which cannot be detected by our observations may not give so much contribution to the flux. This means that comparison of the evaporation rate estimated by the eddy-correlation method with those by other methods will be meaningful.

The estimation of evaporation rate by the eddy-correlation method is made as follows: the data of every 1 sec-mean of $w'$ and $q'$ obtained by the procedures mentioned in the section 3 are applied to Eq. (1), and summed up over 5 min interval. The results are listed in Table 3 as $E(EC)$ in mm unit. The other methods give the evaporation rate by using the data listed in Table 2. The following formulae are taken up here:

Thorthwaite-Holzman's formula [1939],

$$E(TH)=\frac{\rho k^2(u_2-u_1)(q_1-q_2)}{\left(\ln\frac{z_2}{z_1}\right)^2}. \quad \cdots\cdots\cdots\cdots(6)$$

Montgomery's formula [1940],

$$E(Mo)=\rho k u_* \Gamma_1 (q_0-q_1), \quad \cdots\cdots\cdots\cdots(7)$$

Heat-balance method,

$$E(HB)=\frac{1}{\varepsilon}\frac{S-B}{1+\beta}, \quad \cdots\cdots\cdots\cdots(8)$$

where $u$ is the wind velocity, $u_*$ the friction velocity, $q$ the specific humidity, $k$ Karman constant, $\Gamma$ the evaporation coefficient, $\varepsilon$ the latent heat of vaporization, $S$ the net radiative heat transfer, $B$ the heat transfer through the underlying layer downwards, $\beta$ the Bowen ratio, $z$ the height of measuring level above the

Table 3. Estimated evaporation rate [$\times 10^{-2}$ mm (5 min)$^{-1}$]

| Run No. | $E(EC)$[1] | $E(TH)$[2] | $E(Mo)$[3] | $E(HB)$[4] | Pan |
|---|---|---|---|---|---|
| F-1 | 1.81 | 1.58 | 1.25 | 0.57 | |
| F-2 | 1.82 | 1.86 | 1.30 | 2.34 | |
| F-3 | 1.41 | 1.58 | 1.44 | 2.69 | |
| F-4 | 1.66 | 1.16 | 2.05 | 5.43 | |
| F-5 | 0.73 | 0.45 | 1.67 | 2.74 | |
| F-6 | 1.26 | 1.15 | 2.02 | 2.41 | |
| F-7 | 1.30 | 1.88 | 2.21 | 2.44 | |
| F-8 | 1.37 | 0.72 | 1.65 | 1.77 | |
| F-9 | 0.65 | 1.62 | 2.17 | 2.48 | |
| F-12 | 0.70 | 0.49 | 1.80 | 1.35 | |
| Mean[5] | 1.27 | 1.25 | 1.76 | 2.42 | 2.50[6] |
| F-13 | −0.05 | 2.08 | | | |
| F-14 | 0.02 | 2.19 | | | |
| F-15 | 0.56 | 0.26 | | | |
| F-16 | 0.73 | 0.69 | | | |
| F-17 | 0.15 | −0.05 | | | |
| F-18 | 0.04 | −1.02 | | | |
| U-11 | −0.85 | −0.93 | | | |
| U-12 | 0.09 | −0.68 | | | |
| U-13 | −1.34 | −1.40 | | | |
| U-14 | −0.23 | −1.00 | | | |

[1] Esimated by eddy-correlation method.
[2] Estimated by Thornthwaite-Holzman's formula.
[3] Estimated by Montgomery's formula.
[4] Estimated by heat-balance method.
[5] Mean value from Run F-1 to Run F-12.
[6] Total value from $12^h55^m$ to $15^h55^m$.

surface and the subscript 0 indicates value at the surface, 1 and 2 indicate the specified level, respectively.

The results obtained by these formulae are listed in Table 3, including those by the pan method. A surprising agreement between the mean values of $E(EC)$ and $E(TH)$ can be seen in Table 3. This agreement seems not to be accidental, since comparison of the individual values of each run shows also relatively good agreement as shown in Fig. 7. In the case of small value of $E(EC)$, some discrepancies appear between $E(EC)$ and $E(TH)$, as seen in Fig. 7. It may be caused by the relatively large error in measuring the vertical profile of mean temperature in those cases. The error may give also large error in determination of the specific humidity gradient necessary to the calculation of $E(TH)$. It can be concluded that in the unstable and near-neutral conditions the results by Thorthwaite-Holzman's formula give fairly good agreement with those by the eddy-correlation method. From theoretical viewpoint, the former formula is valid only in the neutral case. But it is found that the formula gives reasonable results also in the unstable case. The reason may be found in the presumption that our measuring levels are too low to be sensitive to the effects of non-neutral conditions. It is suggested that Thorthwaite-Holzman's formula which can be applied through fairly simple procedures will be useful to the estimation of evaporation rate unless the measuring levels are higher than 2 m or so.

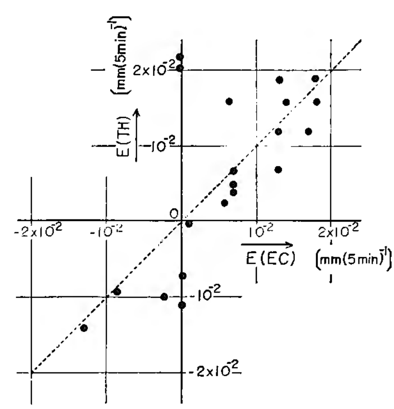


Fig. 7. Comparison between estimated values of evaporation rate by the eddy-correlation method [$E(EC)$], and by the Thornthwaite-Holzman's formula [$E(TH)$].

The results of heat-balance method [$E(HB)$] has poor agreement with $E(EC)$. It must be noticed that the application of this method for a short time interval of 5 min is inadequate. It is the case particularly in determination of the value of $B$ in Eq. (8), because estimation of the stored heat in the body of the water may be impossible in such a short time interval without large error. In order to avoid such error, estimation of the term $B$ is attempted not for each run, but for whole time interval from the run F-1 to the run F-12, or 3 hours. For the other terms in Eq. (8), the values averaged over the same interval are used. The result of such re-calculation gives us the value of $0.91 \times 10^{-2}$ mm/5 min, which approaches remarkably to the value of $E(EC)$.

The results of the pan method listed in Table 3 is corrected for the surface temperature difference between the inside water of the pan and the environmental free water under the assumption that the evaporation may be largely controlled by the gradient of the specific humidity near the water surface, which is largely dependent upon the surface temperature. After such correction is made, there still remain somewhat large discrepancies as seen in Table 3. This may be resulted from the inherent difference of wind structure near the water surface between inside and outside of the pan.

Exclusive of the pan data, the results of other four methods coincide with each other under the error of 50% or less.

## 5. Conclusions

It is attempted to show that the eddy-correlation method is feasible in the actual estimation of the vertical water vapour flux or evaporation rate, using the system of newly developed sonic anemometer and a fine thermocouple psychrometer. In spite of the effects of rather long sound path length of the anemometer, large time constant of wet-bulb thermometer and relatively short sampling duration, it is concluded that the system can give a reasonable results for the estimation of evaporation rate, from the viewpoint of some spectral consideration of the humidity fluctuation and the vertical component of velocity.

Some of the convensional methods are taken up for comparative purpose, and it is shown that Thornthwaite-Holzman's formula gives the best result for various meteorological conditions. This simple formula must be useful for the rough estimation of evaporation rate, if the observation is carried out at the height lower than 2 m or so.

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