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APPLICATION OF SONIC ANEMOMETER-THERMOMETER TO THE STUDIES OF VERTICAL EDDY TRANSPORT PROCESSES IN THE ATMOSPHERIC BOUNDARY LAYER

By

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Abstract

Fundamental problems and limitations of the application of the sonic anemometer-thermometer to the study of the eddy transport of physical entities in the atmospheric boundary layer are discussed. The sonic anemometer-thermometer is most promising equipment for this purpose, but its character and limitation should be borne in mind on the way of application. The main points are line-averaged character of the sensor and humidity dependence of the temperature indications. Applications to the measurement of vertical eddy transport of particular physical entities are discussed respectively.

1. Introduction

Estimation of vertical eddy transport of physical entities in the atmospheric boundary layer is one of the most fundamental problems in physics of the atmosphere, because they define the boundary conditions of the atmospheric behaviour at the bottom. However, meteorologists have been prevented by difficulties in measuring techniques from the direct estimation of the transport. Most of the works concerning the estimation have been performed by indirect method basing upon some assumptions on the atmospheric characters. As this method has an inherent uncertainty and is not expected to give so accurate and reliable results that they are required in the studies of the atmospheric motions, necessity of development of the direct method has been emphasized. Some researchers have endeavoured to find out reasonable means of the direct measurements (for examples, Swinbank [1951] and Dyer [1961]). But the difficulties in measurement of vertical wind velocity has still remained, and reliability of measurement of the eddy transport has not so remarkably been improved.

The recently developed sonic anemometer-thermometer can measure accurately the wind velocity component along the direction of the sensor axis under various conditions from extremely low speed to stormy winds with high response character to rapid change of wind velocity. Moreover, fluctuations of the air temperature can simultaneously be measured with the same sensor (Mitsuta [1966 a]). And it can be anticipated that this instrument may give a great improvement in accuracy and reliability of direct estimation of eddy transports. Experimental researches on application of a sonic anemometer-thermometer to this problem have started quite recently independently in U. S. S. R. (Gurvich and Tsvang [1960] and Gurvich [1961]) and U. S. A. (Kaimal and Businger [1963]). They were, however, too enthusiastic in making use of this epoch-making instrument to investigate the fundamental problems of its application.

The present author has been developing sonic anemometer-thermometer independently (Mitsuta and Mizuma [1964] and Mitsuta [1966 a]), and a new system for direct measurement of eddy transport with a sonic sensor has been proposed (Mitsuta, et. al. [1967]). In this paper, the possibility and fundamental limitation of sonic sensors in application for studies of eddy transport are investigated and some results of preliminary observations are given.

2. Fundamental requirements

Fundamental requirements for the sensors for use in the measurement of vertical eddy transport are mainly concerned with their accuracy and response in the fluctuation measurements. These requirements will be discussed in this section. The vertical eddy transport of a physical entity (X) over a uniform and flat surface is approximated as follows (Swinbank [1951]):

$$F=\overline{(\rho w)'X'}, \tag{1}$$

where F is the magnitude of vertical eddy flux, ρ the air density and w vertical wind velocity component, respectively. The primes denote the departures of quantity from the time mean value shown by bar.

For the purpose of vertical eddy transport measurement, fluctuating values of vertical mass flow (ρw) and concentration the entity (X) should be evaluated in appropriate accuracy. The observed vertical wind component should be exactly the component velocity free from the horizontal component. The former is, in general, quite smaller than the latter, and even a small coupling of the both components produces great errors in measurement of the vertical velocity. Sensors for the both entities (ρw and X) should have enough quick response character to resolve all the fluctuations which are effective for transport processes. Dependency of the eddy flux upon eddy size has been discussed by several meteorologists (Priestley [1956], Deacon [1959] and MacCready [1962]). The critical eddy size, smaller eddy than which has no appreciable contribution to eddy transport, might be identical with the limit below which the eddies

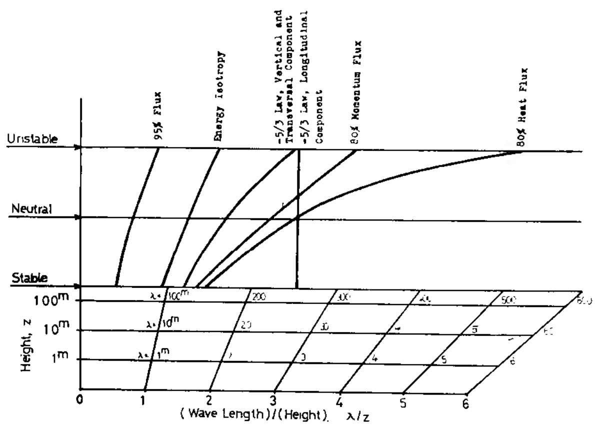

Fig. 1. Criteria for large eddy limits of inertial sub-range near the ground. The scaling of the abscissa, in wave length, changes a little with height. Curves showing criteria on various asumptions are based on the results by MacCready [1962] and Deacon [1959].

become isotropic or the large-eddy end of the inertial subrange. The criteria for the large-eddy limit of the inertial subrange in the air layer near the surface are summarized in Fig. 1, which is mainly based upon the results of MacCready [1962] and Deacon [1959]. The critical eddy size or wavelength is given in the form of the ratio of wavelength to the height above the surface as a function of the height and the thermal stability. The curves of 80% and 95% limits show the wavelength above which 80% and 95% of the total fluxes are found, respectively. The fluctuations below these limits are isotropic and not so effective for transport processes. These results permit us to conclude that the sensors have to resolve the fluctuations of short wavelength at least not less than $0.4z$ in order to measure the total eddy transport within 5% accuracy in all stability conditions, where z denotes the height above the surface.

The response characters of the both sensors should be matched each other in every cases. If the time constants might be different, there must be some frequency ranges in which output of the both sensors are differently delayed in phase, and the product of them involves an imaginary component of cross-spectrum. This frequency range might be found between the equivalent frequencies of the both time constants. In order to keep the difference of the phase lags within 10°, the ratio of the time constants must be smaller than 2 under the assumption of the first-order response character of the sensors. This restriction may not, in general, be so severe, if the unexpected noises of the products caused by the difference of the time constants may vanish on time average, because the quadratic spectral density of vertical velocity and the entity under consideration may be relatively smaller than cospectral density

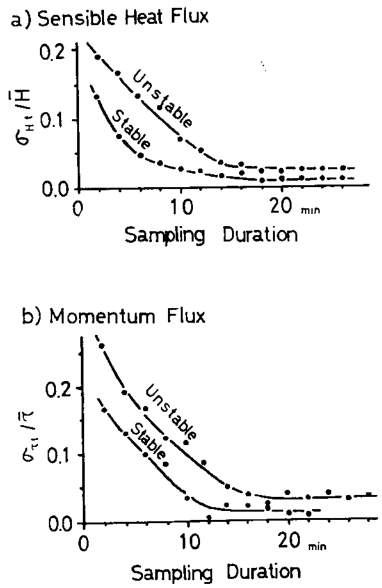

Fig. 2. Dependence of relative deviation of flux estimates (standard deviation of the estimates/mean flux over long period) on the sampling duration at the height of 4 m above the ground. After Chou [1966]

in most cases.

The total sampling duration should be decided by the purpose of the study and the environmental conditions of the observation. It must not, however, be too short to eliminate statistical randomness in the results. Chou [1966] has studied on the fluctuations of $\overline{(w'T')}$ and $\overline{(w'u')}$ sampled over relatively short duration, where T and u are the air temperature and horizontal component of wind velocity along the prevailing wind direction, respectively. His results are summarized in Fig. 2, which shows how the standard deviation of two kinds of cross-terms decreases with sampling duration. It is clear that the optimum sampling durations for measurement of vertical eddy transports of heat and momentum at height of 4 m are 16-18 min for unstable stratification and 14-15 min for stable case, respectively. It may be concluded that total sampling duration should be at least as long as about 20 min in order to avoid statistical fluctuations of observational results near the surface.

3. Performance of the sonic anemometer-thermometer

One of the most remarkable feasibilities of the sonic anemometer-thermometer for the study of vertical eddy transport is that the vertical wind component can be measured directly in a linear scale unlike other traditional sensors such as hot-wire anemometer or anemometer-bivane.

Sonic anemometer-thermometer has no moving part, and wind measurement can be made, in principle, instantaneously by electronic means free from any mechanical inertia. The measurement is actually performed more frequently than one hundred times a second. Response character of this instrument as a wind sensor is, however, limited from another point. It is a geometrical restriction resulted from a line-averaging character of the sensor (Mitsuta [1966a]). Attenuation of short-wavelength fluctuations by the averaging over a certain length, d, can be evaluated according to the moving averaging procedure by Pasquill [1962].

Considering a fluctuation as composition of sinusoidal components, let the variation, y, associated with a component of wavelength λ be represented by

$$y = a \sin(2\pi x/\lambda). \tag{2}$$

The averaging process over a finite length, d, means replacement of y in Eq. (2) by

$$y' = 1/d \int_{x'-d/2}^{x'+d/2} y dx = \frac{a\lambda}{\pi d} \sin(\pi d/\lambda) \sin(2\pi x'/\lambda) \tag{3}$$

This indicates that the averaging process brings about reduction of the amplitude of sinusoidal variation by $\frac{\lambda}{\pi d}\sin(\pi d/\lambda)$. This reducing factor can be applied for estimation of attenuation by a sonic sensor with path length of d. This path length is, in practice, in the range from 5 to 100 cm. As small eddies in this range can be assumed to be isotropic, this reducing factor can be applied to fluctuations in any directions. Fig. 3 shows the variation of this reducing factor with wavelength, which is just the same as that deduced by frozen eddy hypothesis (Mitsuta [1966a]).

Fig. 4 shows examples of power spectra of vertical velocity component observed at the heights of 1.5 and 3.0 m above the bare soil surface by a sonic anemometer with path length

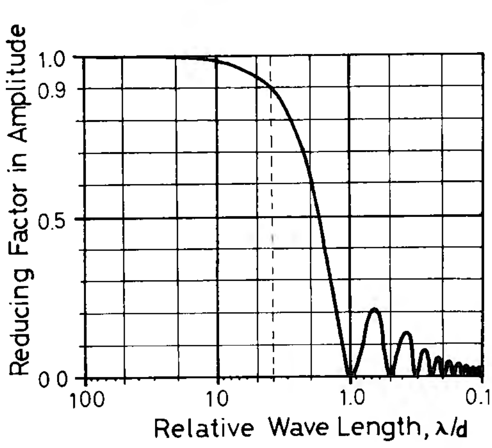

Fig. 3. Variation of the reducing factor of amplitude with relative wave length (wave length, λ/sound path length, d).

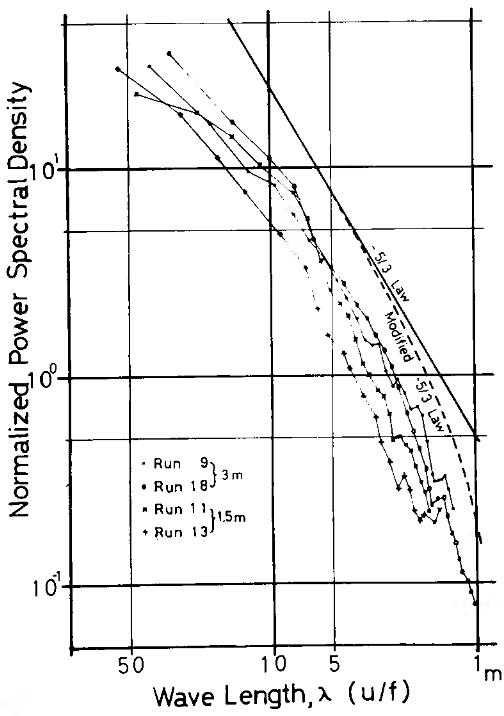

Fig. 4. Normalized power spectra of the vertical wind velocity components observed by a sonic anemometer with path length of 50 cm. The dotted line shows $-5/3$ law modified for attenuation caused by the line averaging character of the sound path length.

of 50 cm. The range of wavelength shorter than 10 m or so in this case is clearly within the inertial subrange where the spectra are expected to obey the so-called minus five-thirds law. The most of the observed spectra follows this law fairly well, except short-wavelength end where the spectra deviate somewhat to the smaller side from the law. This deviation can be almost explained by the attenuation character of the sensor mentioned above, and actually the observed spectra obey the modified minus five-thirds law with the reducing factor shown in Fig. 3.

It can be concluded from Figs. 1 and 3 that the sonic anemometer with sound path length shorter than 50 cm may be used for the study of eddy transport at the level higher than about 4 m above the surface. And the sound path length should be shorter than 5 cm when an observation will be carried out at the height of 40 cm. These limits of the path length may, however, be doubled, if we can allow loss of 10 % in flux estimate.

The performance stability and noise level of the sonic anemometer should be enough good not to produce any intolerable errors for a long term observation, which is often needed for the climatological study of eddy transport or air-earth surface interaction. To see the worst conditions the old vacume tube type sonic anemometer described in the previous paper (Mitsuta [1966 a]) was operated in a small calm chamber in the room without air conditioning for the term longer than 10 days. Even though the air temperature inside the room varied in the range as large as 20°C, from about 0°C to 20°C, the overall drifts of zero point and the change of full-scale calibration in this period were quite small. Short-period random fluctuations of 1 cm/sec in r. m. s., which were overlapping on long-period change of 3.3 cm/sec in r. m. s., are seen. The maximum drift rate of zero point was only 6 cm/sec for 30 min. The r. m. s. value of zero-point fluctuation in the analogue output circuit itself was only 2.2 cm/sec and that of full-scale calibration was 0.4 % of the full scale 3 m/sec in this case. These characteristics are almost within tolerable limit, because the r. m. s. value of vertical velocity component is larger than a few tens cm/sec in most cases.

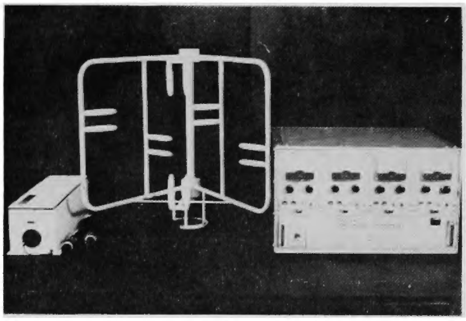

Fig. 5. The improved type of sonic anemometer-thermometer in all solid state circuit, which measures three dimensional components of wind velocity and air temperature. The three sound paths are 20 cm in length and two horizontal ones are crossing in 120°.

For the improved type of sonic anemometer-thermometer with solid-state circuit completed just recently, the performance character of the electronic component is remarkably improved by the order of ten. Outlook of this new instrument is shown in Fig. 5. The wind anttena (sensor) has three sound paths of 20 cm in length to measure simultaneously three-dimensional wind components and temperature. The electronic component is very compact and the weight is only 15 kg. The details of this new instrument will be described in another paper.

4. Applications

a) *Momentum transport*

Vertical eddy transport of momentum can be detected by combination of horizontal and vertical sonic anemometer sensors. The magnitude of downward transport is defined as

$$M=-\overline{(\rho w)'u'}, \tag{4}$$

where u' is fluctuating component of horizontal wind velocity in the direction under consideration.

The sonic anemometer measures the product of the air density and the velocity rather than the velocity itself. And the indication is calibrated for the standard air density or air temperature, and for 1.205×10^{-3} g/cm^3 or 20°C for the present instruments. Thus, the indicated vertical wind velocity, w_i, and the true velocity, w, are related each other as follows:

$$\rho_s w_i=\rho w, \tag{5}$$

where ρ_s is the standard air density. This relation also holds well for horizontal wind component, u. For the measurement of momentum transport, the true velocity u is needed rather than u_i, and some temperature correction should be applied to u_i. The correction factor designated as K_T in the previous paper (Mitsuta [1966 a]) is reproduced in Fig. 6. The sound virtual temperature used in this figure is a new parameter introduced by Baret and Suomi, and is defined by the temperature and humidity as shown by the Eq. (26) in the Section 4, and its dependency on temperature and humidity is il-

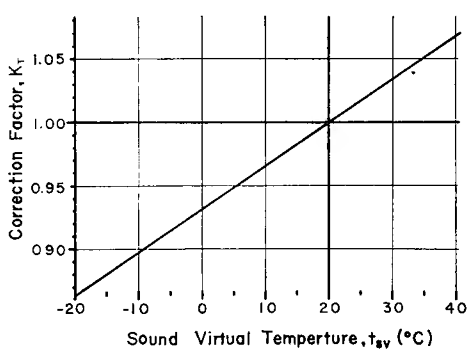

Fig. 6. Variation of temperature correction factor, K_T of sonic anemometer with sound vertual temperature, t_{sv} (°C). After Mitsuta [1966 a]

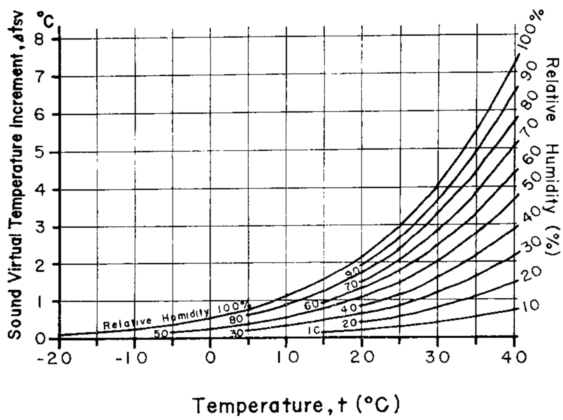

Fig. 7. Variation of sound virtual temperature increment, Δt_{sv} from air temperature, t ($t_{sv}=t+\Delta t_{sv}$) with air temperature and humidity. After Mitsuta [1966 a]

lustrated in Fig. 7. Thus, the momentum flux is obtained by the relation;

$$M=-K_T\rho_s\overline{w_i'u_i'}, \tag{6}$$

from the indications of sonic anemometers.

To arrange the sensor so as to parallel with the mean wind direction is laborious and often erroneous operation in actual field works. This shortcoming is removed by the use of three dimensional sensor with two horizontal and one vertical sensing paths. The mean wind direction α from one of the horizontal axes, X is defined by using two rectangular components, u_x and u_y as follows;

$$\cos\alpha=\frac{\bar{u}_x}{\sqrt{\bar{u}_x^2+\bar{u}_y^2}},\quad \sin\alpha=\frac{\bar{u}_y}{\sqrt{\bar{u}_x^2+\bar{u}_y^2}}, \tag{7}$$

The instantaneous wind velocity component in the direction of mean wind, U is given as follows;

$$u=\sqrt{\bar{u}_x^2+\bar{u}_y^2}+u_x'\cos\alpha+u_y'\sin\alpha, \tag{8}$$

The momentum transport is, then, defined as

$$\left.\begin{aligned}M&=-\overline{(\rho w)'u'}\\&=-\overline{(\rho w)'u_x'}\cos\alpha-\overline{(\rho w)'u_y'}\sin\alpha\\&=\frac{1}{\sqrt{\bar{u}_x^2+\bar{u}_y^2}}(\bar{u}_xM_x+\bar{u}_yM_y),\end{aligned}\right\} \tag{9}$$

where $M_x=-K_T\rho_s(\overline{w_i'u_i'})$ and $M_y=-K_T\rho_s(\overline{w_i'u_i'})$, respectively. And the total momentum transport can be obtained from the two component transports by this equation.

The sonic sensor shown in Fig. 5 has a crossing angle of 120° between the two horizontal components. These two components u_1 and u_2 can be reduced into rectangular components u_x and u_y by the following relation:

$$\begin{cases} u_x = u_1 + u_2 \\ u_y = \dfrac{1}{\sqrt{3}}(u_2 - u_1). \end{cases} \tag{10}$$

The co-ordinate systems taken here are shown in Fig. 8. This correction should be applied to the instaneous values before processing.

Some results of test observation of momentum transport are shown in Table 1. This observation was carried out at Shionomisaki and the details will be reported in another paper (Mitsuta [1968]).

In the practical procedure of observation, it must be remembered that the sensor for the vertical velocity observation should be kept exactly in vertical. Even an angle of 1° from the vertex might yield an error of vertical velocity by about 2% of horizontal velocity, and the error is nearly equal to 5%, because the vertical eddy velocity component is usually about one half or one third of the horizontal component.

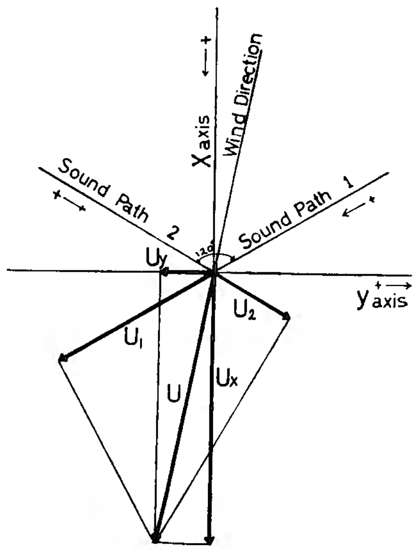

Fig. 8. Coordinate system of wind composition of two wind components measured by two horizontal sensing paths crossing in 120°.

Table 1. The results of the direct observations of momentum flux with sonic anemometers and a drag meter. At Shionomisaki.

Run	Date & Time of Start	Sampling Duration	Surface	Mean Wind Speed (1.5m)	Momentum Flux	95% Limit of M. Flux	Surface Drag
		min		m/sec	dyne/cm²	cps	dyne/cm²
S	Jan. 13, '66 03h 35m	6	lawn	4.4	5.3 (at 2m)	—	1.7
10	Dec. 22, '66 11h 49m	5	bare soil	3.9	2.5 (at 3m)	0.50	0.7
11	Dec. 22, '66 12h 26m	5	b. s.	3.8	1.4 (at 1.5m)	0.83	—
12	Dec. 22, '66 13h 08m	5	b. s.	4.0	1.3 (at 3m)	0.50	—
13	Dec. 22, '66 13h 56m	5	b. s.	4.4	2.0 (at 1.5m)	0.42	0.8
27	Dec. 22, '66 11h 38m	15	b. s.	6.8	2.7 (at 1.5m)	0.44	1.4

b) *Kinetic energy transport*

Vertical eddy transport of kinetic energy can be also detected by three-dimensional combination of sonic sensors. The total kinetic energy of unit mass is defined as

$$\left.\begin{aligned} k &= 1/2\cdot[(\bar{u}+u')^2+v'^2+w'^2] \\ &= 1/2\cdot\bar{u}^2+u'\bar{u}+1/2\cdot(u'^2+v'^2+w'^2), \end{aligned}\right\} \tag{11}$$

where x axis is along the mean wind direction. Thus, the vertical eddy transport of kinetic energy can be written as follows:

$$\left.\begin{aligned} K &= \overline{(\rho w)'k'} \\ &= \overline{(\rho w)'\{u'\bar{u}+1/2\cdot(u'^2+v'^2+w'^2)\}} \\ &= \overline{(\rho w)'u'}\bar{u}+\overline{1/2\cdot(\rho w)'(u'^2+v'^2+w'^2)}. \end{aligned}\right\} \tag{12}$$

The first term in the right-hand side is the product of the vertical transport of momentum and the mean wind speed, which means flux of kinetic energy of the mean flow. The last term is the vertical flux of eddy kinetic energy. Thus, the equation (12) is reduced to

$$\begin{aligned} K &= -M\bar{u}+1/2\cdot\overline{(\rho w)'(u'^2+v'^2+w'^2)} \\ &= -M\bar{u}+1/2\cdot K_T\rho_s\overline{w_i'(u_i'^2+v_i'^2+w_i'^2)}, \end{aligned} \tag{13}$$

where M is the downward transport of momentum, defined in (4).

The results of test observation at Shionomisaki are shown in Table 2 (Maitani and Mitsuta [1967]). The magnitude of eddy kinetic energy transport is only about 5 to 10 % of kinetic energy transport of mean flow, and their transports are in opposite direction in the examples shown in this table.

Table 2. The results of direct measurement of kinetic energy flux at the height of 3 m over bare soil with sonic anemometers (positive upward), At Shionomisaki,

Run	Date & Time of Start	Sampling Duration	Mean Wind Speed		Richarson Number	$-M\cdot\bar{U}$	$\overline{1/2(\rho w)'\times(u'^2+v'^2+w'^2)}$
			1.5 m	6 m	1.5–6 m	3 m	3 m
		min	m/sec	m/sec		cgs $\times10^3$	cgs $\times10^2$
23	Dec. 24, '66 15h 46m	15	4.6	5.7	−0.02	−1.69	2.10
25	Dec. 25, '66 12h 12m	13	4.7	5.7	−0.02	−3.76	1.16
29	Dec. 26, '66 15h 23m	3	7.0	7.8	0.01	−2.40	1.96

c) *Vorticity transport*

Direct measurement of vorticity and its transport is one of the unique applications of the sonic anemometer. This application was originally developed by the present author (Mitsuta [1966 b]). Three sonic sensors are arranged in a triangle form in the vertical plane along the mean wind direction. By adding three component velocities multipied by the side length of the triangle in the cyclic sense, we can obtain the circulation along this small triangle. Dividing it by the area of the triangle, vorticity can be deduced. A schematic diagram and a result of test observation at Uji are shown in Fig. 9 (Mitsuta [1966 b]).

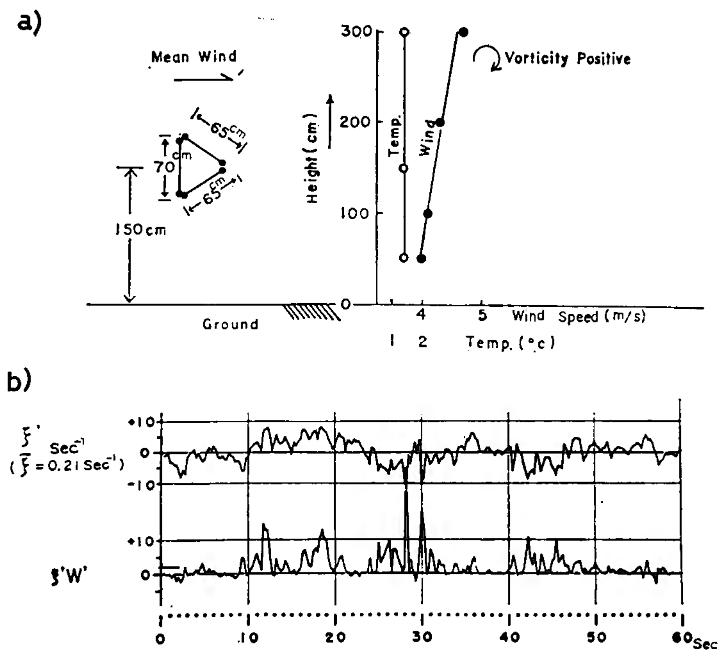

Fig. 9. a) Observational scheme and b) Time changes of vorticity and its vertical transport near the ground. After Mitsuta [1966 b]

The circulation C is defined as

$$C = l_1 u_1 + l_2 u_2 + l_3 u_3, \tag{14}$$

where l is the side length of the triangle and u being the component velocity along the side. Thus the vorticity, ξ can be obtained by

$$\xi = C/A = (l_1 u_1 + l_2 u_2 + l_3 u_3)/A, \tag{15}$$

where A is area of the triange. As the mean vertical motion within this triangle is approximated by

$$w = (u_1 - 2Au_2/l_1 l_2 - 2Au_3/l_1 l_3)/2, \tag{16}$$

where l_1 is length of the vertical side, and l_2 and l_3 are those of slant sides, respectively. The vertical eddy transport of vorticity, V, is written as follows :

$$\left.\begin{aligned} V &= \overline{(\rho w)'\xi'} \\ &= (K_T\rho_s/2A)\overline{(u_i'{}_1 - 2A/l_1l_2 \times u_i'{}_2 - 2A/l_1l_3 \times u_i'{}_3)} \\ &\quad \overline{\times (l_1u_i'{}_1 + l_2u_i'{}_2 + l_3u_i'{}_3)}. \end{aligned}\right\} \tag{17}$$

The mean vorticity measured by sonic sensors was $+0.21\,\mathrm{sec}^{-1}$ and was nearly identical with that expected from the mean wind profile $+0.20\,\mathrm{sec}^{-1}$ in the case of Fig. 9. And the sense of the transport was upward.

d) Sensible heat transport

The vertical eddy transport of sensible heat, H, is defined as

$$H = c_p\overline{(\rho w)'T'}, \tag{18}$$

where c_p is the isobaric specific heat of the air and T the air temperature, respectively. The air temperature can be simultaneously detected by a sonic anemometer-thermometer. But the indication of the sonic thermometer is not, in general, exactly the same as true air temperature, T, but sound virtual temperature, T_{sv} defined by referring to sound speed (Mitsuta [1966 a]). The difference of these temperatures becomes too large to overlook in estimating the sensible heat transport in very humid conditions (Okamoto [1966]). Lumley and Panofsky [1964] have pointed out that the sensible heat transport is contributed also by water vapor and the effect can be taken account in an approximate way by replacing the true air temperature, T with the virtual temperature, T_v, which is related to T through the specific humidity, m,

$$T_v = T(1 + 0.61\,m). \tag{19}$$

Then, the sensible heat transport becomes

$$H = c_p\overline{(\rho w)'T_v'}. \tag{20}$$

Expanding the equation (19) and neglecting the small terms, the fluctuating component of T_v is approximated as follows:

$$T_v' = T' + 0.61\,\overline{T}m'. \tag{21}$$

Thus, the sensible heat transport is given by

$$H = c_p\overline{(\rho w)'T'} + 0.61 c_p\overline{T}\,\overline{(\rho w)'m'}. \tag{22}$$

The first term on the right-hand side is the ordinary sensible heat transport for dry air. The factor of the second term $\overline{(\rho w)'m'}$ is the vertical eddy transport of moisture which is equal to the rate of evaporation, E, from the surface. Then, we have, using a new expression H_d for the H in equation (18)

$$H = H_d + 0.61\,c_p\overline{T}E. \tag{23}$$

And using the Bowen ratio B defined by

$$B = H_d/LE, \tag{24}$$

the above equation becomes

$$H = (1+0.61\, c_p \overline{T}/LB) H_d, \tag{25}$$

where L is the latent heat of evaporation. This equation implies that the true sensible heat transport H in the humid condition is somewhat different from the value of H_d for dry condition.

While the temperature indication of sonic thermometer or sound virtual temperature T_{sv} is defined as

$$T_{sv} = T(1+0.52\, m), \tag{26}$$

where the relation $m=0.622\, e/p$ is assumed, and e and P are water vapor pressure and the atmospheric pressure, respectively. The product of the fluctuating components of the sound virtual temperature and vertical mass flow defines the *sonic* sensible heat transport, H_s expressed as

$$\left.\begin{aligned} H_s &= c_p\overline{(\rho w)'T'} + 0.52\, c_p \overline{T}\,\overline{(\rho w)'m'} \\ &= H_d + 0.52\, \overline{T} E. \end{aligned}\right\} \tag{27}$$

By use of the Bowen raio it is reduced to

$$H_s = (1+0.52\, c_p \overline{T}/LB) H_d. \tag{28}$$

The *sonic* sensible heat transport H_s might be, in humid condition, quite different from the value of H_d, depending on value of B, but is nearly equal to the actual sensible heat transport H. The difference between H_s and H is about 10% or so, even when the Bowen ratio is as small as 0.1 like over the ocean surface. This shows feasibility of the sonic anemometer-thermometer for measurement of the sensible heat transport even in humid condition.

e) *Water vapor transport*

The vertical eddy transport of water vapor in the air layer near the surface, which is a fair estimation of evaporation from the surface, can be detected by a sonic anemometer with the aid of an appropriate sensor of water vapor concentration. Water vapor sensor should have compatible response character with that of sonic anemometer. For this purpose, the present author and his collaborator have developed an infrared absorption hygrometer with sensing path of the same length as that of sonic anemometer (Chen and Mitsuta [1967]). Considering that the wind velocity measurement is less affected by humidity, the water vapor transport is expressed as follows:

$$E = \overline{(\rho w)'m'} = \rho_s \overline{w_i' m'}, \tag{29}$$

where the specific humidity m is measured directly by the infrared hygrometer.

Table 3. The results of direct measurement of water vapor flux with sonic anemometer and infrared absorption hygrometer. At Shionomisaki.

Run	Date & Time of Start	Sampling Duration	Mean wind Speed (1.5m)	Air Temp. (1.5 m)	Vapor Pres. (1.5m)	Water Vapor Flux (1.5m)	95% Limit of Flux
		min	m/sec	°C	mb	mm/hr*	cps
221	Dec. 24, '66 10h 00m	10	3.8	12.8	7.8	0.13	0.47
222	Dec. 24, '66 12h 00m	5	5.3	14.2	8.0	0.10	0.25
223	Dec. 24, '66 14h 00m	6	5.1	14.4	7.5	0.06	0.75
224	Dec. 24, '66 16h 00m	8	4.2	12.9	7.6	0.18	0.40
225	Dec. 24, '66 18h 00m	2	6.5	11.0	7.3	0.08	0.38
226	Dec. 24, '66 23h 00m	3	5.4	8.9	7.1	−0.04	0.08

* shown in liquid water equivalent.

In this measurement matching of the time constants of both sensors should be fulfiled. And the sensing paths of the sonic and infrared sensors should be placed as closely as possible in the process of measurement.

Some results of test experiment are shown in Table 3 (Chen and Mitsuta [1967]). In this experiment, a sonic anemometer with 50 cm sound path and infrared hygrometer with equal sensing path are used. The time constant of the infrared hygrometer is as large as a few tenths of second, and the sonic data were smoothed by moving average technique over 0.5 sec. The 95% limit of water vapor transport, which is estimated from cospectra of w and m, is about 0.5 cps in frequency or 8 m in wavelength in the daytime of evaporation case, and about 0.1 cps or 40 m in the nighttime of condensation case, respectively.

This measurement of water vapor transport is one of the most promising method for estimating the evaporation rate from various kinds of surface, because it is based upon no inherent assumption.

5. Conclusions

The sonic anemometer-thermometer can be a reliable sensor in the study of the vertical eddy transport near the surface, if the limitation of response or sensitivity is carefully considered in process of measurement. The sonic anemometer should be used above the height which is determined by referring to the sound path length of the anemometer. A temperature correction is not needed for the vertical mass transport measurement, but for the measurement of velocity component and other kinematical measurement. The time constants of sonic anemometer and the sensors of other fluctuating components should be matched each other. Although the implication of sensible heat transport measured by sonic anemometer-thermometer is different from that expected in the dry air, the former is nearly equal to the actual transport of the sensible heat. The sonic anemometry gives a promising system of estimating the evaporation rate from the surface by the aid of some appropriate sensor of moisture content. Possibility and feasibility of the sonic anemometer-thermometer to the vertical eddy transport are confirmed by several test observations.

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