A new sensitive eddy flux instrumentation

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ABSTRACT

An instrument for direct measurement of the turbulent water vapour flux has been constructed and used in a field program in southern Sweden. The instrument consists of wet and dry bulb platinum resistance elements of Australian design and of a new fast response wind instrument. The instantaneous wind vector is measured by the aid of strain gauges fixed to elastic plates, exposed to the wind pressure. The signals from the probes are recorded photographically by a mirror galvanometer with free period 0.05 sec. With this galvanometer vertical velocities are recorded with an accuracy of ± 0.01 m/s, when the wind speed is not too low.

The evaluation of the photographic recordings being highly time consuming, a device has been constructed which at least reduces the time required for the evaluation by a factor of ten.

The efficiency of the flux record is controlled by the time constant of the wet bulb element which is of the order 0.5 sec. Then according to DEACON almost full recovery is obtained in lapse conditions but only c. 80 % in inversion conditions.

Experimental data is presented from 45 successful 30–60-min measurements. Computed water vapour flux data is presented as well as complementary micrometeorological data.

Background

During the years 1955–1963 a cooperative investigation of the hydrological conditions at the Kristianstad plain in south Sweden was performed (see WEIJMAN-HANE, 1961). This investigation includes detailed precipitation studies (ELLESON & PERSSON, 1961), studies of the ground water (LARSSON, 1962), of the run off, of the evaporation and of many other aspects of the hydrological problem. Many Swedish institutions were involved. The Swedish meteorological and hydrological institute was responsible for the run off studies and for the evaporation studies. This paper is the first one in a series of four which will report results of more general interest from the evaporation studies.

The problem set forth at the planning of the evaporation studies was this: To obtain, if possible, a continuous evaluation of the natural evaporation at a selected place with the aid of the flux gradient method. That is, the evaporation should be evaluated from the formula:

$$E = -\varrho K \frac{\partial \bar{s}}{\partial z}, \qquad (1)$$

where E means water vapour flux, ϱ density of the air, K the exchange coefficient for water vapour and $\partial \bar{s}/\partial z$ the vertical gradient of specific humidity. But this means that K must be known explicitly at any meteorological condition. Because of the rather incomplete information available on this point—at least in the middle of the fifties when the investigation started—it was decided that an instrument for direct recording of the eddy flux should be developed. The instrument should be run in selected situations, giving samples of the order of an hour of length. From this information, as well as from simultaneous measurements of $\partial \bar{s}/\partial z$ (and of other micrometeorological variables), K could then be derived with the aid of eq. (1).

This paper gives a description of the turbulence instrumentation that was thus developed and applied. It also gives a table of the raw data obtained at 45 successful experiments, each 30 to 60 min in length, performed at

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Ugerup, situated about 10 km south of the town of Kristianstad. In a forthcoming article the data will be analysed in order to obtain the exchange coefficients. In a third article there will be presented the results of a continuous evaluation of the natural evaporation over a period of more than two years with the aid of eq. (1) and the exchange coefficients obtained. The series of papers on the evaporation at Ugerup will be ended up with an article in which an attempt to evaluate the water balance is presented.

General construction of the turbulence instrumentation

The *sensing unit* is reproduced in Fig. 1. It consists of a centrally placed wind instrument and of a wet and a dry bulb element, placed c. 50 cm apart at the opposite ends of a rod, which is held in a direction approximately perpendicular to the wind by a rather large vane.

The *wind instrument* is of an entirely new construction and will be described in detail in the next section.

The *wet and dry bulb elements* have been built from Australian drawings. A slightly different type of elements have been shortly described by McIlroy (1955 and 1961).

The wet and the dry bulb elements are geometrically similar, with the exception that the wet bulb element has a tank for distilled water at the bottom. The sensing element of the dry bulb consists of 600 Ω 0.001 inch bare platinum wire, helically wound on a network of wicks, mounted on a light plastic frame, about 7 cm high and 10 cm in diameter. The platinum wire of the wet bulb element is closely twisted with a fine cotton thread, the effective diameter being about 0.005 in. This wet bulb wire is then wound helically exactly as the bare platinum wire of the dry bulb element.

The wet bulb wire has been manufactured by CSIRO in Australia and kindly supplied by them.

The *recording instrument* used in a mirror galvanometer called "Ultragraph" (manufactured by AB Svensk Malmletning). The instrument as a whole is very handy (approximate dimensions 50 cm × 30 cm × 15 cm), because the light beams from the galvanometer mirrors are reflected several times before it reaches the photographic paper, where the signals are recorded. This paper is of 150 mm width. During the experiments, the paper is fed at a rate of 2 cm per second. The paper used is of the kind used for X-ray photography, which is not very sensitive to daylight though very well for the ultraviolet light of the galvanometer beam. On the recording paper four signals are being recorded simultaneously: two from the wind instrument and one from each of the wet and dry bulb elements. The galvanometers used have slightly different sensitivity. A representative figure is 13,000 mm/mA. The free period is c. 0.05 sec.

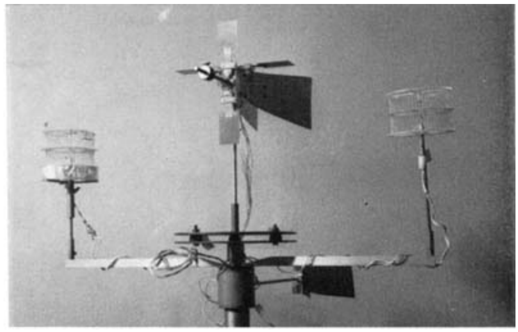

Fig. 1. The eddy flux instrumentation. Wind sensing unit is placed centrally. Dry and wet bulb elements are situated on each end of a rod, which is held in approximately perpendicular direction to the wind by a large vane.

The wet and the dry bulb elements are each connected in Wheatstone bridge, fed from dry cells. The measuring current used is 1, 2 or in some cases 4 milliamperes. With 2 mA a temperature change of 1°C corresponds to about 39 millimeters on the recording paper. Only temperature *deviations* are measured. Thus the bridge is adjusted before the experiment starts so that the corresponding curve will remain on the recording paper.

The wind instrument

As seen from Fig. 1, the wind instrument has the shape of a wind vane with two pairs of plates at the head, one pair being placed vertically, the other horizontally. The instrument is about 20 cm in length. The vane is made of thin aluminium and has a small counter weight in the nose so that the whole instrument is well balanced in respect to the vertical axis, around which it operates in small bearings.

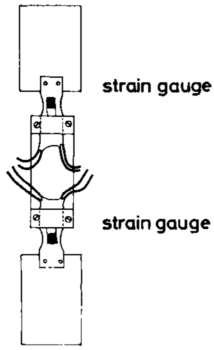

Fig. 2. A pair of wind pressure sensing plates. The outer rectangular plates are clinched to elastic beryllium copper plates, which in its turn is fixed to the central plastic block. The bending of the beryllium copper plates is transmitted to electrical signals by strain gauges glued on both sides of the plates as shown in the figure.

When the instantaneous wind vector is strictly horizontal it exercises a dynamical pressure on the pair of vertical plates only. When the wind vector is inclined to the horizontal, both pairs of plates are affected. A pair of plates is displayed in Fig. 2. The wind pressure sensing plates are of rectangular shape, 36 mm × 54 mm. They are made out of superpertinax, 0.5 mm thick. These plastic plates are attached to 0.3 mm thick plates of beryllium copper, which is firmly connected to a plastic frame that forms part of the vane. On both sides of the elastic beryllium copper plates strain gauges have been glued. The four 600 Ω strain gauges of one pair of plates form the four arms in a Wheatstone bridge. The bridge is fed from dry cells (4.5–15 volt).

The plates have been calibrated in a wind tunnel, the free stream speed being measured with a pitot tube. Fig. 3 gives, on the ordinate, the wind speed by perpendicular attack and, on the abscissa, the corresponding deflection of the "Ultragraph". The line drawn corresponds to

$$V = a\sqrt{x}, \tag{2}$$

where V is wind speed, x the deflection and a a calibration constant. Fig. 4 shows how the deflection depends on the angle of attack. The ordinate gives the quotient $x_\varphi/x_\perp$, where x_φ means the deflection when the angle of attack is φ and $x_\perp$ means the corresponding deflection at perpendicular attack, the wind speed being

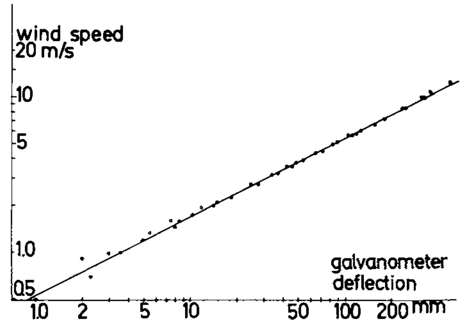

Fig. 3. Wind tunnel calibration of a pair of plates at perpendicular attack of the wind vector. The line drawn corresponds to $V = a\sqrt{x}$, where V is the wind speed and x the galvanometer deflection. This analytic form is the same for all specimens of plates, but the constant is individual. The constant is most easily found for a new specimen by comparing the galvanometer deflection after putting a known weight on the wings of both the new specimen and the one already calibrated. Such a test against a reference specimen is also always performed before and after an experiment.

the same. At these tests the pair of plates is turned around its *length axis*, which is always kept perpendicular to the wind. Quite another calibration curve is obtained when the pair of plates is turned round an axis in the plain of the plates but perpendicular to the length axis. With the arrangement of the plates used in the ensemble instrument, as shown in Fig. 1, the

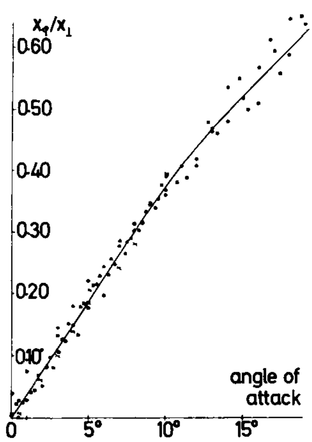

Fig. 4. Galvanometer deflection, x_φ at angle of attack φ, divided by the deflection at perpendicular attack, $x_\perp$, at the same wind speed. Different symbols indicate calibrations performed at different wind speeds in the range 4–8 m/s. The quantity $x_\varphi/x_\perp$ is clearly independent of wind speed.

wind vector has nearly always a direction sufficiently perpendicular to the length axis for the results of Fig. 4 to be applicable. Fig. 4 is based on several calibrations in the wind speed range 4.0 to 8.5 m/sec. There is no evidence of a wind speed dependence in the quotient x_φ/x.

The scatter of the calibration points of Figs. 3 and 4 is noticeable, but not very considerable. In Fig. 3 the scatter is by far greatest at low wind speeds. This is simply due to the fact that the deflection then only amounts to one or a few millimeters. At high wind speeds a certain uncertainty arises from the fact that the elasticity of the strain gauge glued beryllium copper plates is not perfect. It means that after changing from a rather high wind speed to zero speed, it will take a certain time for the plates to go back to real "zero state". This effect, however, seems not to have a very important implication on the reproducibility of the results.

When the instantaneous wind vector is horizontal, the pair of vertical plates give a deflection x, and from eq. (2) $x = V^2/a^2$. The deflection arising from the horizontally oriented plates, z is in this case zero. If the wind vector is inclined an angle φ to the horizontal,

$$x = V^2/a_1^2 \cdot f(90° - \varphi), \tag{3a}$$

$$z = V^2/a_2^2 \cdot f(\varphi), \tag{3b}$$

where $f(\varphi) = x_\varphi/x_\perp$. The horizontal and vertical component of the wind vector is obtained respectively as

$$V_H = V \cos \varphi, \tag{4a}$$

$$w = V \sin \varphi. \tag{4b}$$

In Fig. 5 the thick curve is the function $f = f(\varphi)$ taken from calibrations over the entire interval 0–90°. The thin curve drawn is $f(\varphi)/f(90° - \varphi)$. The broken curve is 2.22 sin φ. Then with very good accuracy for $|\varphi| \leq 10°$:

$$\frac{f(\varphi)}{f(90° - \varphi)} = 2.22 \sin \varphi. \tag{5}$$

But from eq. (3):

$$\frac{f(\varphi)}{f(90° - \varphi)} = \frac{z}{x} \frac{a_2^2}{a_1^2}. \tag{5a}$$

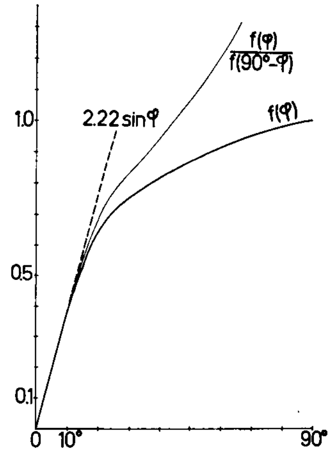

Fig. 5. The thick curve, labelled $f(\varphi)$, represents for the whole range of angles the best fit of the calibration results for $x_\varphi/x_\perp = f(\varphi)$ (individual calibration points are plotted in Fig. 4 for the range $\varphi <$ c. 20°). As to the other two curves, see the text.

This together with eq. (3a), (4b) and (5) gives:

$$w = \frac{a_2^2}{\sqrt{f(90° - \varphi)} \cdot a_1 \cdot 2.22} \cdot \frac{z}{\sqrt{x}}. \tag{6}$$

Now $\sqrt{f(90° - \varphi)}$ differs from 1.0 by less than 0.01 when $|\varphi| \leq 10°$ so that eq. (6) becomes:

$$w = \frac{a_2^2}{2.22 a_1} \cdot \frac{z}{\sqrt{x}}, \tag{7}$$

where thus a_1 and a_2 are instrumental constants and x and z are the galvanometer deflections from the vertically and horizontally oriented pair of plates respectively. With the same approximation as above

$$V_H = a_1 \sqrt{x}. \tag{8}$$

A typical value for a_1 and a_2 is 0.5 ms^{-1}/mm$^{1/2}$. Thus the practical lower limit for the measurement of the horizontal velocity component is in the neighbourhood of 1 m/s or just below. Vertical velocities, however, can be safely recorded down to much lower values. If for instance $x = 100$ mm, which corresponds to $V \approx 5$ m/s, vertical velocities of the order of 0.025 m/s can be recorded with confidence (cf. eq. (7)), which corresponds to angular deviations from the horizontal of the order of 0.25°. The resolution is greater in practice because the instrumental constant a is always greater than

a_2 in the experimental set up used. Thus it seems realistic to consider w to be measured with an accuracy of ± 0.01 m/s, when the horizontal wind exceeds 3 or 4 metres per second. At such speeds V_H is given with an accuracy of about ± 0.02 m/s.

The response-time of the instrument is very short. The free period is about 0.05 sec. This period can sometimes be recognized in a very fine ripple on the records from the plates.

The approximation which led to eq. (7) for w is chiefly that given by eq. (5). This approximation is quite satisfactory for $|\varphi| \leq 10°$ (see Fig. 5). Of course this approximation is not *necessary* for the evaluation of w. When the quotient z/x is known from the recording, $f(\varphi)/f(90° - \varphi)$ is given from eq. (5a). Then φ can be drawn from the experimental curve (the thin line) in Fig. 5, and V, V_H and w can be computed from eqs. (3) and (4). But this is a very time-consuming procedure, especially when one has to evaluate a great number of values, as is the case when computing turbulent fluxes. To obtain an idea of how the approximate eq. (7) might work in a real case, the angle φ was computed for a great number of points from a record made at moderate instability at a height of about 4 meters above a corn field. The evaluation showed that 94% of all φ-values were less than 10°. In these cases the sine-function differs from the true function by less than 1%. Only in 1.5% the computed w-values differed from the true ones by more than 6%. As seen from Fig. 5, the *modulus* of the computed values are always *greater* than the real values. On the whole, the effect of the adopted approximation on computed fluxes must be small.

The instrument described above is not the first one which makes use of strain gauges for wind measuring purposes. CHEPIL & SIDDOWAY (1959) has reported on an instrument based on this principle. This instrument, however, was different from ours in important respects. For turbulent flux measurements instruments based on widely different principles have been used. SWINBANK (1955) applied a hotwire anemometer. Later the Australians have developed a heat transport anemometer of apparently very good performance, R. J. TAYLOR (1958) and DYER (1960). The Soviet scientists have used a kind of hot wire anemometer, OBUCHOW (1958) and later an acoustic anemometer (GURVICH, 1965). Panofsky *et al.*, see for instance PANOFSKY (1962), has employed aerovanes and bidirectional vanes. The new wind instrument, described in this article, is clearly equally suited for turbulent flux measurements as the best ones used by others. The instrument is however not so well suited for high frequency *turbulent fine structure* studies, mainly because of the dimensions of the instrument.

The drawbacks of the new wind instrument lies mainly on the following points:

(1) complex evaluation,

(2) the imperfectness in elasticity of the glued beryllium copper plates may cause certain troubles,

(3) the instrument cannot be used in case of precipitation, not even in the form of dew fall because the "wings" will then be loaded with water droplets.

The evaluation problem can be easily overcome, if the signals are recorded by an electronic data logging system, which will be the case in a forthcoming project, now being on the way.

The problem of elasticity imperfectness can be controlled, if several zero point checks are taken during the course of an experiment. This was done in the case of the 45 experiments of Table 1.

The difficulty of performing sensitive turbulence measurements in precipitation conditions shares the new instrument with probably all earlier instruments.

Evaluation

To evaluate fluxes from direct measurements of the four curves on the photographic recordings is extremely time-consuming. Because of this a special evaluation device was constructed. A photograph of the device is reproduced in Fig. 6. It shows a slanting table over which the photographic record is transported with a constant speed. In the plane of the table, but perpendicular to the transportation direction, two indices can be moved independently of one another. The movement of an index is achieved by turning one of the big wheels situated on each side of the slanting table. Two operators can follow one curve each with these indices, while the record is transported with constant speed in the direction it has been recorded. The indices are connected each to a circular cylinder on the mantle of which is fixed a fine metal thread, which slides along a linear electrical resistance, when the index is moved and thus

Table 1. *Experimental data from the Ugerup site.*

Legend: E = water vapour flux in $\mu g\ cm^{-2}\ s^{-1}$. Ri_4 = Richardson number at 4 m level $= g/\theta[\partial\theta/\partial z/(\partial\bar{u}/\partial z)^2]$, the gradients being taken from curves of best fit for the temperature and wind respectively. Φ = practical stability parameter $= \Delta\Theta_m/U_m^2$, where $\Delta\Theta_m = 1/3\,[(\Theta_{12}+\Theta_{6.4}+\Theta_{3.4})-(\Theta_{1.8}+\Theta_{0.95}+\Theta_{0.5})]$ and $U_m = 1/6\,(U_{12}+U_{6.4}+U_{3.4}+U_{1.8}+U_{0.95}+U_{0.5})$, where the indices of Θ and U give the height in metres; the values are taken from curves of best fit. The U- and T-values of the table are the original measured values, the indices giving the height in metres above ground.

No.	Date and time	E μg $cm^{-2}s^{-1}$	Ri_4	Φ	$U_{0.75}$	$U_{1.5}$	U_3	U_6	U_{12}	$T_{0.5}$	$T_{1.5}$	$T_{4.5}$	$T_{11.7}$	State of ground
	1961													
4	24/7 11	3.50	−0.052	−0.046	2.85^a	3.50^b	3.60	4.40	5.15	17.0	16.7	16.3	16.0	Corn, 70 cm high
6	3/8 19	0.21	+0.151	+0.345	1.30^a	1.60^b	1.65	2.20	2.85	13.1	14.0	14.5	14.7	
10	13/8 20	0.11	+0.098	+0.165	1.30	1.75	—	2.40	3.30	11.3	11.6	12.0	12.2	
12	17/8 10	2.92	−0.670	−0.353	—	—	1.40	1.65	2.10	17.6	17.0	16.6	16.2	
13	17/8 13	4.30	−0.200	−0.155	—	—	2.30	2.75	3.40	20.5	19.8	19.4	18.8	
16	20/8 12	2.62	−0.045	−0.023	4.25	4.90	4.95	5.80	6.90	18.2	17.6	17.4	16.9	
	1962													
1	11/5 19	0.35	0	+0.011	2.15	2.45	2.65	2.85	—	8.2	8.3	8.3	8.2	Corn 5 cm high
2	13/5 13	4.50	−4.70	−0.154	2.25	2.45	2.60	2.60	—	10.3	9.5	8.9	8.5	
3	16/5 12	3.36	−0.051	−0.017	4.00	4.45	4.50	5.00	5.70	10.4	10.1	10.0	9.7	
4	16/5 16	4.10	−0.031	−0.010	3.30	3.75	3.90	4.55	4.65	11.2	11.2	11.1	10.8	
5	16/5 19	1.02	+0.170	+0.099	2.40	2.70	2.65	3.10	3.75	8.7	9.3	9.7	9.7	
7	17/5 11	5.98	−0.074	−0.028	4.00	—	4.55	5.25	5.65	14.3	14.0	13.5	13.0	
8	9/7 15	6.57	−0.710	−0.515	0.95	1.15	1.20	1.30	1.75	21.5	20.6	20.4	20.0	Corn 70 cm high
9	10/7 10	9.45	−0.115	−0.104	1.75	2.25	2.45	3.00	3.55	21.0	20.4	20.1	19.8	
10	10/7 14	8.50	−0.170	−0.212	1.40	1.80	1.85	2.25	2.90	24.5	23.8	23.5	23.0	
11	11/7 11	5.96	−0.900	−0.611	1.00	1.25	1.30	1.35	1.45	20.5	19.5	19.0	18.8	
12	11/7 18	0.93	0	+0.042	1.50	2.00	2.35	2.70	3.30	16.8	17.0	17.1	17.0	
13	11/7 22	0.31	+0.180	+0.151	—	1.20	1.50	1.60	2.10	14.2	14.4	14.6	14.5	
14	12/7 06	1.28	−0.150	−0.305	0.75	1.05	1.20	1.45	2.30	15.4	15.0	14.7	14.5	
15	12/7 13	3.34	−0.031	−0.041	2.70	3.75	4.05	4.75	5.35	20.2	19.5	19.2	18.8	
16	12/7 16	3.02	−0.057	−0.026	1.95	2.60	2.70	3.20	3.80	18.3	18.2	18.0	17.9	
17	13/7 09	2.25	−0.430	−0.308	1.05	1.35	1.45	1.60	2.05	17.4	16.8	16.5	16.2	
18	10/8 11	2.50	+0.013	+0.016	2.50	4.40	5.10	6.00	6.60	15.4	15.6	15.8	15.8	
19	11/8 10	4.40	0	0	2.50	4.45	5.15	6.25	7.35	16.0	16.0	15.9	15.9	
20	11/8 13	2.00	0	0	2.40	4.00	4.50	5.40	6.35	16.8	17.0	16.9	16.8	
21	12/8 17	2.20	0	0	2.35	3.90	4.50	5.40	6.40	18.9	19.2	19.1	19.0	
22	12/8 18	0.64	+0.036	+0.049	1.65	3.05	3.45	4.10	5.05	17.3	17.9	18.1	18.2	
23	13/8 06	2.49	−0.013	−0.019	1.75	3.15	3.35	4.10	4.95	13.7	13.5	13.4	13.3	
24	13/8 08	3.37	−0.020	−0.025	1.75	3.10	3.50	4.25	5.25	14.7	14.4	14.3	14.1	
25	13/8 10	4.10	−0.028	−0.022	1.95	3.50	3.65	4.35	5.50	15.8	15.7	15.5	15.3	
26	13/8 12	2.28	−0.007	−0.007	1.85	3.30	3.95	4.85	5.70	15.2	15.2	15.1	14.9	
27	13/8 15	3.58	−0.019	−0.013	2.00	3.55	3.90	4.60	6.05	16.4	16.3	16.2	16.0	
28	13/8 18	0.93	+0.017	+0.043	1.85	(3.35)	3.35	3.95	5.75	13.9	14.4	14.6	14.5	
29	14/8 14	6.68	−0.025	−0.042	1.85	(3.35)	3.30	4.00	4.55	17.8	17.3	17.0	16.7	
30	14/8 17	2.73	−0.043	−0.050	1.30	2.30	2.25	2.40	3.65	16.7	16.4	16.3	16.1	
	1963													
1	26/9 11	3.60	—	−0.006	—	—	—	—	8.0	13.4	13.2	13.3	13.0	Recently ploughed field
2	27/9 09	0.23	−0.009	−0.007	3.60	5.05	5.40	6.35	7.35	12.7	12.6	12.6	12.3	
3	28/9 10	3.03	−0.018	−0.024	2.80	3.85	4.25	5.10	6.05	12.8	12.2	12.1	11.9	
4	28/9 15	1.14	—	−0.010	—	—	—	—	7.8	13.4	13.2	13.4	13.0	
5	28/9 16	0.44	+0.011	+0.011	2.75	3.75	4.45	5.30	6.40	12.1	12.4	12.7	12.4	
6	30/9 15	1.64	−0.013	−0.014	2.85	3.80	—	—	5.75	12.7	12.4	—	12.2	
7	30/9 17	0.40	+0.020	+0.060	1.75	2.40	2.85	3.30	4.35	8.8	9.5	—	9.6	
8	1/10 07	1.14	0	0	2.00	2.70	2.95	3.50	4.40	9.3	9.2	—	9.2	
9	1/10 10	1.23	−0.016	−0.014	2.55	3.50	3.75	4.50	5.50	10.7	10.5	—	10.2	
10	1/10 11	2.09	−0.023	−0.027	2.55	3.50	3.75	4.50	5.50	11.6	11.1	—	10.7	

[a] Level of measurement 1.44 m.
[b] Level of measurement 2.1 m.

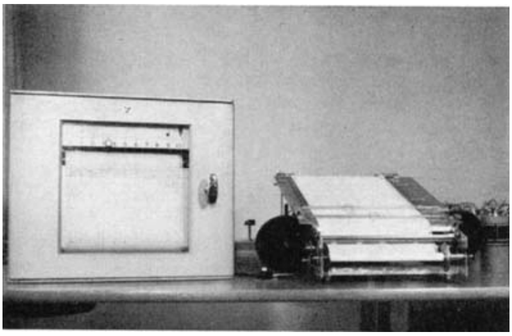

Fig. 6. Evaluation device. The photographic record is transported with constant speed along the slanting table, seen to the right in the figure. Two persons operate simultaneously each one index, which can be moved in a direction perpendicular to the direction of the transportation of the recording paper. An electrical signal which is linear in w, e or in (ew) is obtained as result of the evaluation—see the text and Figs. 7 and 8—and fed to the potentiometer recorder to the left in the figure.

the cylinder turned. The contact threads can be fixed as suitable curves on the mantles of the cylinders. It is then possible by simple electrical connections to obtain an output signal from the evaluation system which is proportional to w, when the indices follow the x- and z-signals from the wind instrument (see Fig. 7). In that case the contact thread for the x-signals has the form $1/\sqrt{x}$, cf. eq. (7). The output signal, which is thus linear in w, is fed to a potentiometer recorder seen to the left in Fig. 6.

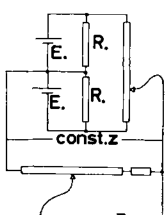

Fig. 7. Principle of the electrical circuit for evaluating the vertical velocity $w = \text{const.}\ z/\sqrt{x}$ from signals x and z. The sliding contacts are each in the form of a metal thread fixed on a cylinder, the turning of which is achieved by the movement of one of the indices of the evaluation device (see Fig. 6). The contact threads are so arranged on the respective cylinders that in one case a turning x gives a displacement of the contact proportional to $1/\sqrt{x}$ and in the other case a turning z gives a displacement proportional to z.

The vapour pressure is evaluated in a similar way, after changing the contact cylinders and the electrical connections. The operators then follow the T- and T_w-signals respectively with their indices. The vapour pressure is evaluated from the psychrometric equation:

$$e = \bar{e} + A(\bar{T}_w) \cdot T_w - BT, \tag{9}$$

where $\bar{e}$ is the mean vapour pressure for the whole record. A is given a value appropriate to the mean wet bulb temperature of the record so that the saturation vapour pressure curve is approximated by a straight line in the range of the T_w-values of the record. B is given a constant value. The contact curve form for both the T_w- and T-record is linear. Fig. 8 gives the principle of the electrical circuit. The output signal, which is thus linear in e, is recorded on the same paper as w, but with another colour of the ink, the starting line of the two curves (e and w) coinciding, and the paper speed being the same in the two cases. The synchronization of the two curves is checked at regular intervals.

The product (ew) is evaluated from the new recording paper in a similar way as w and e were evaluated from the original photographic record. The same circuity as for w (Fig. 7) is used, but with linear contact curves. The output signal, which is thus linear in (ew) is recorded on the potentiometer recorder on a new paper. The speed of this paper is such that 1 sec of the *original record* corresponds to 5 mm of the (ew)-paper. The covariance $\overline{ew}$, which is proportional to the water vapour flux, has been evaluated by measuring the deflection at regular 5 mm intervals.

With the method described above it will take about one working day for two persons to evaluate fully a record of length 30 to 60 min. To obtain the same result by picking up values direct from the original recording and then per-

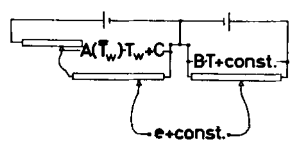

Fig. 8. Principle of the electrical circuit for evaluating the water vapour pressure, $e = A(\bar{T}_w) \cdot T_w - B \cdot T + \text{const}$, from signals T_w and T. The movement of the sliding contacts is achieved by the movement of the two evaluation indices—see the legend of Fig. 6 and the text.

forming all the computations involved on a desk calculator will take more than ten working days for two persons.

Accuracy of the recorded flux

The water vapour flux is evaluated as:

$$E = -\frac{1}{R_v T}\overline{w'e'}, \tag{10}$$

where R_v is the gas constant for water vapour. The errors in the determination of this quantity assign to the following two categories:

(1) instrumental inaccuracy,

(2) evaluation errors.

Apart from occasional errors, the most important inaccuracy of the instrumentation lies in the time constant of the slowest part, which by far is the wet bulb element. McIlroy (1961) states the following values for his version of this instrument:

$$\tau_i = 0.2 \text{ sec for } \overline{V} \geqslant 6 \text{ m/s},$$

$$\tau_i = 0.4 \text{ sec for } 6 > \overline{V} \geqslant 3 \text{ m/s},$$

$$\tau_i = 0.6 \text{ sec for } \overline{V} < 3 \text{ m/s}.$$

The present author has not made any proper attempt to evaluate τ_i for the instrument used. Inspection of the records, however, indicates that McIlroy's values might be somewhat too high for this instrument. Deacon (1959) and McIlroy (1961) have studied the influence of smoothing on the flux-measuring efficiency. They give the percentage efficiency of flux measurement as a function of the quantity $\tau\overline{V}/z$, where τ is smoothing time, $\overline{V}$ mean wind speed and z height above ground. When the free period, τ_g, of the galvanometer is the controlling factor, τ in the expression $\tau\overline{V}/z$ is substituted by 0.5 τ_g (see Deacon, 1959). When the instrumental time constant, τ_i is the most important time constant $\tau = 2.5\ \tau_i$, according to Deacon. In our case $\tau_g \approx 0.05$ sec, but the biggest $\tau_i \approx 0.4$ sec. (cf. above). Then the abscissa quantity of Deacon's (1959) Fig. 1 is about 1.0 for typical conditions, z being about 4 m. Then the flux recovery is

$> 95\%$ for lapse conditions,

c. 92% for neutral conditions,

c. 80% for inversion conditions,

There are several potential sources of error in the evaluation procedure. The most important ones are summarized below.

(1) The flux is evaluated as a sum of point values from the (we)-curve. Evaluations have shown that the standard deviation of the (we)-curve is about twice the mean value. Then the standard error in $\bar{E}$ is

$$\delta\bar{E} \approx \pm\frac{2\bar{E}}{\sqrt{n}}, \tag{11}$$

where n is the number of values and $\bar{E}$ the computed flux for the whole experiment. In most cases n was of the order of 1000 or 2000 so that the relative error will be about $\pm 5\%$.

(2) Inaccuracy in the zero-line position for the (ew)-record. An inaccuracy of ± 0.5 mm gives an inaccuracy in $\bar{E}$ of about $\pm 5\%$.

The other evaluation errors are probably of minor importance for the flux:

(3) Inaccuracy in the mean value for T_w (giving the slope of the saturation vapour pressure curve). If the inaccuracy is supposed to be ± 1°C, the error in e, δe:

$$\delta e = \pm 1.2\% \text{ at } T_w = 20°\text{C},$$

$$\delta e = \pm 1.6\% \text{ at } T_w = 8°\text{C}.$$

(4) When computing $(w'e')$ it is very important that the influence of an erroneous mean vertical wind, $\overline{w}$ is eliminated. This is achieved by computing the mean values from the curves for e and w respectively. An error of 1 mm in each of $\bar{e}$ and $\overline{w}$ gives a total error $\pm 0.5\%$ in $\bar{E}$.

To sum up, the evaluation errors which are independent of each other and occasional, form a total error in $\bar{E}$ which is of the order of $\pm 7\%$.

Turbulent water vapour flux measurements of this accuracy have up to now only been presented by Dyer (1961) and by Dyer & Pruitt (1962).

Experimental data

Table 1 contains data from 45 successful experiments, performed during three summers at the experimental site at Ugerup, each experiment having a length of between 30 and 60 min. The site is not quite ideal in a micrometeorological sense (it was chosen as typical agricultural land). The land is level and mainly covered with crop. About 200 m north of the place where the turbulence measurements took place in

1962 and 1963, in a separate mast, c. 4 m high, there are some houses belonging to a farm. There are also hedges of various height (2–7 m). In other directions there are scattered groups of trees and more distant groups of farm houses. A fairly large sector is however undisturbed for many kilometres, and *most of the experiments are carried out with wind coming from this sector.* No experiments are carried out with winds coming from the direction of the nearby farm.

The flux experiments of 1961 were not performed at the spot described above. They were carried out on a permanent, 12 m high mast, situated c. 100 m closer to the farm houses. In this mast wind- and temperature-profiles and a humidity difference were measured all the three summers. The vegetation of the site was the same as that of the surroundings. It changed from year to year and also from spring to autumn—see the last column of Table 1 for details. Measurements of the neutral wind profile show a corresponding change in the roughness parameter, z_0

(1) corn 75 cm: $z_0 = 6.5$ cm

(2) corn 5 cm: $z_0 = 1$ cm

Wind was measured continuously at 12 m and during the experiments at 5 heights (0.75 m, 1.5 m, 3 m, 6 m and 12 m, except for some early experiments—see the table). The anemometer used was of type Fuess "Schalen-Handanemometer" with small and light cups, moving in a diameter of about 5 cm. The five instruments used were calibrated in field by running them parallel at the same height. The performance of the instruments is fair, but they do not fulfill very high demands.

Temperature was measured with ventilated platinum-thermometers at four heights: 0.5 m, 1.5 m, 4.5 m and 11.7 m. The temperatures were recorded on a potentiometer recorder (Siemens Kompensograph) and could be read to the nearest 0.1°C.

Humidity was measured at two heights, 1.5 m and 11.7 m. with Lambrecht hair-hygrometer with "Pernix-hair". The humidity, as well as the temperature, was checked regularly (ca 300 times in 30 months) with Assmann psychrometer in the mast. It was found that the standard deviation of the determination of the vapour pressure difference, Δe, was as high as ± 0.37 mb. The *mean* Δe for those experiments carried out in unstable conditions was 0.49 mb and for those carried out in neutral and inversion conditions $\overline{\Delta e} = 0.33$ mb. It is thus no sense to use the individual Δe-values in connection with the measured fluxes to derive exchange coefficients. So the Δe-values are omitted from Table 1. As will be shown in a forthcoming article this difficulty is overcome, by putting the flux data together in a number of stability groups, and only using the abovementioned mean values for Δe, so obtaining the exchange coefficient as a function of stability. In another forthcoming article will be shown how the exchange coefficients can be derived on a running basis from measurements of a temperature difference and the wind speed at 12 m. Approximate hourly evaporation values can then be computed with the aid of eq. (1) and the Δe-values given. Adding 24 such hourly values gives daily values of fair accuracy and further adding gives still better results for longer periods.

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REFERENCES

CHEPIL, W. S., and SIDDOWAY, F. H., 1959, Strain-gauge anemometer for analysing various characteristics of wind turbulence. *Journ. of Met.*, **16**, p. 411.

DEACON, E. L., 1959, The measurement of turbulent transfer in the lower atmosphere. *Advances in Geophysics*, **6**, p. 211.

DYER, A. J., 1960, Heat transport anemometer of high stability. *Journal of Scientific Instruments*, **37**, p. 166.

DYER, A. J., 1961, Measurement of evaporation and heat transfer in the lower atmosphere by an automatic eddy-correlation technique. *Quart. Journ. of the Royal Met. Soc.*, **87**, p. 401.

DYER, A. J., and PRUITT, W. O., 1962, Eddy flux measurements over a small irrigated area. *Journ. of Applied Met.*, **1**, No. 4, p. 471.

ELLESON, J., and PERSSON, R., 1961, Occasions with unusually great amounts of rain in Scania, Sweden, in 1959–1960. *Svensk Geografisk Årsbok*, **37**, p. 7 (in Swedish, with English summary).

GURVICH, A. S., 1965, Vertical temperature and wind velocity profiles in the atmospheric surface layer. *Izvestiya Atmospheric and Oceanic Physics*, **1**, No. 1 (English edition published by the Amer. Geophys. Union).

LARSSON, I., 1962, Studies on ground water in the quaternary deposits of the Kristianstad plain. *Lund Studies in Geography*, ser. A, Physical Geography No. 19.

McILROY, I. C., 1955, A sensitive temperature and humidity probe. *Australian Journ. of Agricultural Research*, **6**, No. 1, p. 196.

McILROY, I. C., 1961, Effects of instrumental response on atmospheric flux measurement. Div. of Met. Physics Techn. Paper No. 11. Commonwealth Scientific and Industrial Research Organization, Australia.

OBUCHOW, A. M., 1958, Untersuchung der Mikrostruktur des Windes in der bodennahen Schicht der Atmosphäre. *Sammelband zur statistischen Theorie der Turbulenz*, herausgegeben von H. Goering, Akademie-Verlag, Berlin.

PANOFSKY, H., 1962, The budget of turbulent energy in the lowest 100 meters. *Journ. of Geophysical Research*, **67**, No. 8, p. 3161.

SWINBANK, W. C., 1955, An experimental study of eddy transports in the lower atmosphere. Div. of Met. Physics Techn. Paper No. 2. Commonwealth Scientific and Industrial Research Organization, Australia.

TAYLOR, R. J., 1958, A linear, unidirectional anemometer of rapid response. *Journ. of Scient. Instr.*, **35**, No. 2, p. 47.

WEIJMAN-HANE, G., 1961, Investigation of the hydrology in the plain of Kristianstad. A presentation of the programme being undertaken by a research team. Kungl. Väg- och Vattenbyggnadsstyrelsens publikationsserie Pu 8.1 (in Swedish, with English summary).

НОВАЯ ТОЧНАЯ АППАРАТУРА ДЛЯ ИЗМЕРЕНИЯ ТУРБУЛЕНТНОГО ПОТОКА

Создан и испытан в полевых условиях на юге Швеции прибор для прямых измерений турбулентного потока влажности. Прибор состоит из сухого и смоченного платиновых элементов сопротивления австралийской конструкции и нового малоинерционного датчика ветра. Мгновенный вектор скорости ветра измеряется при помощи тензометрических датчиков, приклепленных к эластичным пластинам, на которые воздействует давление ветра. Сигналы датчиков записываются фотографически при помощи зеркального гальванометра со временем установления 0.05 сек. Вертикальная компонента скорости ветра записывается этим гальванометром с точностью $\pm 0{,}01$ м/сек, когда скорость ветра не слишком мала.

Была создана аппаратура, которая уменьшила время, необходимое для обработки фотографических записей, по крайней мере, в 10 раз.

Правильность записи потока контролируется постоянной времени смоченного элемента, порядок которой равен приблизительно 0,5 сек. Тогда, согласно Дикону, при неустойчивой стратификации при измерениях охватывается почти весь поток, а при инверсионных условиях только 80%.

Экспериментальные данные получены из 45 измерений продолжительностью 30–60 мин каждое. Представлены вычисленные значения потока влажности, а также дополнительные микрометеорологические данные.