Mausam, (1983), **34**, 3, 257-262

551.508.79:551.57:631.44

Estimation of Bowen's ratio from temperature and humidity measurements using thermistors and water vapour fluxes over a bare cotton soil

L. K. SADANI and U. P. RAIBOLE*

Indian Institute of Tropical Meteorology, Pune

(*Received 9 December 1981*)

सार–यहां वर्णित उपकरण बावेन अनुपात (β) को मापता है। अर्थात् संवेदी उष्मा और वाष्पन की गुप्त उष्मा के अनुपात को भूस्तर से 1 और 3 मीटर ऊपर लगे शुष्क एवं नम वल्ब तापमानों की सीधी मापों से माप लेता है। β के मापों, कुल विकिरण अभिवाह (R) एवं मृदा उष्मा अभिवाह G का उपयोग करके भूस्तर के निकट वाष्प अभिवाह की गणना की गई। सभी प्रेक्षण फरवरी 1980 की शीत ऋतु में केन्द्रीय कृषि मौसम वधशाला, पुणें में किए गए।

वाष्पन से संबद्ध संहतियों के अभिवाह-मानों (E) की माध्य शीत वर्ग ए-पैन मानों से तुलना की जा सकती है। दूसरी ओर ये मान शरद ऋतु में अनाच्छादित कपास श्याम मृदा के प्रतिदिन के अनुमानित वाष्पन मानों से कहीं अधिक हैं।

ABSTRACT. The instrument described here measures Bowen's ratio (β), *i.e.*, the ratio of sensible heat to latent heat of vaporization, from the direct measurements of dry bulb and wet bulb temperatures taken at 1 and 3 metres a.g.l. Vapour flux near to the ground was calculated using the observations of β, net radiation flux R and soil heat flux G. The observations were taken in the winter season in the month of February 1980 at Central Agromet. Observatory, Pune.

The values of fluxes of mass (E) associated with the evaporation are comparable with the mean winter class A Pan values. However, these values appear to be some what higher than the expected daily bare black cotton soil evaporation values in winter condition.

1. Introduction

The vertical flux of momentum between atmosphere and ground can be considered as a continuous drag force transmitted through the air to produce shearing, or sliding of one layer over another, known as the shearing stress. This force is usually taken as constant with height near to the ground, since under most circumstances only a small fraction is absorbed by any particular air layer, the greater part being transmitted to the air further on.

By analogy with molecular transfer processes a basic equation of mean vertical transfer of momentum can then be written as follows :

$$\tau = \rho \, K_m \, d\bar{u}/dz$$

where τ is the shearing stress, ρ and $\bar{u}$ are the density and time mean horizontal velocity of the air and K_m the eddy transfer coefficient at height z.

Associated with the eddy motions which give rise to a transport of momentum, there must be a similar transport of any other atmospheric property whose average concentration also varies with height. The two most important cases will be briefly mentioned here. They are firstly that of sensible heat and secondly that of water vapour, with an associated transfer of latent heat. Three transport equations can thus be written as :

$$\tau = \rho \, K_m \, d\bar{u}/dz \quad (1)$$

$$Q_H = -C_p \, \rho \, K_H \, d\bar{T}/dz \quad (2)$$

$$L_E = -L \, \rho \, K_w \, d\bar{q}/dz \quad (3)$$

Q_H and L_E are the vertical fluxes of sensible heat and water vapour, K_H and K_w are the respective eddy transfer coefficients, C_p, $\bar{T}$ and $\bar{q}$ are the specific heat at constant pressure, the mean dry bulb temperature and the mean specific humidity respectively all at height z. L is the latent heat of vaporization over water.

*Present affiliation : Oceanography Division, Naval Physical and Oceanographic Laboratory, Cochin.

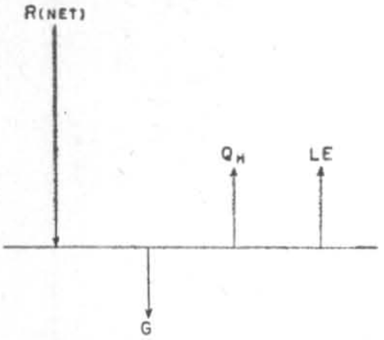

Fig. 1. Meteorological energy fluxes above and below the soil surface, solid ground

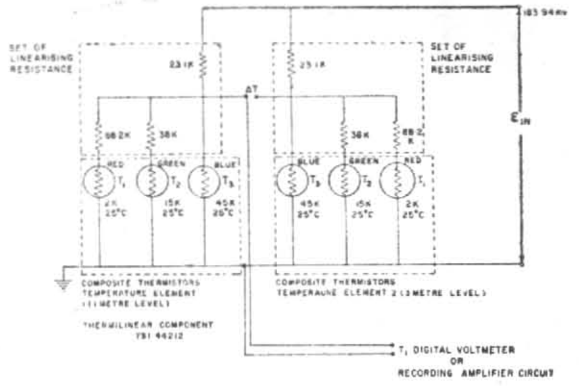

Fig. 2. Circuit diagram for measurement of temperature difference and ambient temperature

From the Eqns. (2) and (3) Bowen's ratio is expressed as :

$$\beta = \frac{Q_H}{L_E} = \frac{-C_p\ \rho\ K_H\ \frac{d\overline{T}}{dz}}{-\ L\ \rho\ K_w\ \frac{d\overline{q}}{dz}} = \frac{C_p K_H\ \frac{d\overline{T}}{dz}}{L\ K_w\ \frac{d\overline{q}}{dz}}$$

$$= \gamma \triangle T / \triangle q \qquad (4)$$

Since heat and water vapour have a common source at the earth surface, it is reasonable to assume that a common transfer mechanism would lead to $K_H = K_w$ where $\gamma = Cp/L$ is the psychrometric constant and $\triangle T$, $\triangle q$ are the differences in air temperature and specific humidity respectively, each measured over the same height interval. However, γ is taken equal to $1.02\ Cp/L$ by Slatyer *et al.* (1961) for fully ventilated thermometers and considering variation of Cp/L (for moist air) with temperature and humidity.

The components of the energy balance at the earth surface (*see* Fig. 1) can be written into the equation,

$$R_{\,(\text{Net})} = L_E + Q_H + G \qquad (5)$$

By transforming and rearranging, we get :

$$\therefore\ R_{(\text{Net})} - G = L_E \left(1 + \frac{Q_H}{L_E}\right)$$

$$\because \frac{Q_H}{L_E} = \beta$$

Therefore, the mass flux of water vapour is given by :

$$E = \frac{R - G}{L} \left(\frac{1}{1+\beta}\right) \qquad (6)$$

The success of Bowen's ratio approach to measure E, depends largely on the accuracy of measurement of $\triangle T$ and $\triangle q$. An instrument developed for such measurement is described in this paper.

2. Instrumentation

(i) Transducers

The dry bulb temperature and the wet bulb temperature differences are measured by using thermistor sensors; the thermilinear component (YSI 44212, 1976). The wet bulb sensors are wetted by moistened wick. One set of the sensors (Dry and Wet) is mounted in a duct (Psychrometer). Similar arrangement with quartz crystal temperature sensors were used by McNeil *et al.* (1975).

The air is sucked through duct at the rate of 4 metres per second by an exhaust fan enabling sensors to be calibrated with consistency (Shwerdtfeger 1976). The duct is painted with titanium dioxide mixed with white paint to reduce the effect of radiation. Two such temperature ducts are mounted on the tower at the height of one metre and three metre levels a.g.l. The thermistor network is diagrammatically shown in Fig. (2).

The equation which best describes behaviour of the above linearised thermistor network is $E_{\text{out}} = (-0.00559149\ E_{\text{in}})\ T + 0.59300\ E_{\text{in}}$ where E_{in} is the supply voltage and T is the temperature in degree Celsius.

The value of supply voltage E_{in} is calculated to set the differential output voltage approximately equal to 1 mv corresponding to 1°C. E_{in} is found to be 178.432 mv but conveniently set to 183.94 mv.

(ii) Circuit theory

The difference analog voltages signal from the temperature sensing circuit is fed to the differential voltage amplifier circuit which amplifies the signal for suitability to the scaling circuit [*see* Fig. (3)].

The output voltages from the differential amplifier circuit are fed to the voltage to current converter. The current converter uses recording

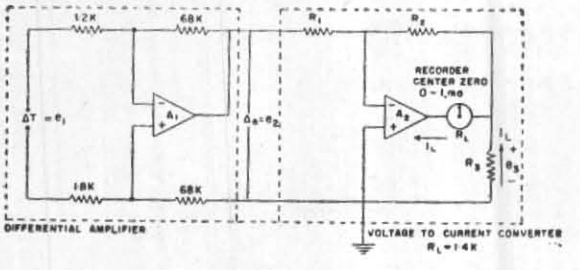

Fig. 3. Differential amplifier and VToC circuit for amplification and scaling

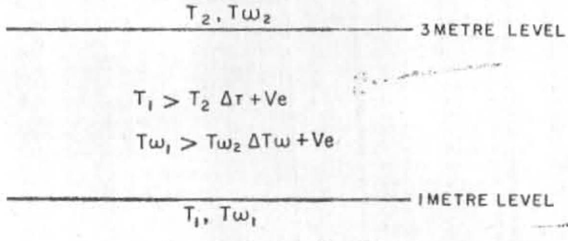

Fig. 4. Mounting levels of the sensors

galvanometer as its resistance load which is of the order of 1400 ohms. Here most of the current is provided by the current converter and only small portion by differential amplifier. Analysis of the circuit yields the following equation for the load current $I_L = \triangle e/R_1 \times (1 + R_2/R_3)$. The resistance R_3 by Graeme *et al.* (1971) provides a convenient means of scaling the current. It is so chosen that each smallest division on the chart paper corresponds to 0.05 ma current which corresponds to 0.11 °C. The recorder is of 1.0 ma full scale deflection with zero centre facility. There are 20 small divisions on the chart paper corresponding to full scale deflection of the recorder. The temperature differences are read from the chart record directly. The temperature system is calibrated for temperature difference within the errors of 0.02°C. The circuit is wired in the manner when $T_1 > T_2$, $\triangle T$ is positive and $T_{w1} > T_{w2}$, $\triangle T_w$ is positive.

(*iii*) *Calibration procedure*

The thermilinear component YSI 44212, Fig. (2), is a composite device consisting of resistors (88.2 K, 38 K and 23.1 K) and precise thermistors (T_1, T_2 and T_3 all combined in one piece by mfr), which produces a voltage linear with temperature shown in the Fig. (2) at point T_1. This output is described by the equation :

$E_{out} = (-0.00559149\ E_{in})\ T + 0.59300\ E_{in}$ (YSI 44212, 1976), in the temperature range —50 °C to 50° C. Its ohomic values at temperatures 20 °C, 25 °C and 30 °C are 1121.2 Ω, 10474.8 Ω and 9825.3 Ω respectively. Its voltage values are obtained against the bath temperatures from 0 to 50 °C with supply voltage of $E_{in} = 183.94$ mv. Four such thermistor composites are calibrated and numbered for the purpose of identification. They are to be calibrated pair-wise so that simultaneously zero differential output can be checked. After bath calibration, place one pair of thermistor composite in a ventilated temperature duct. Among them, one thermistor is identified as a dry bulb temperature sensor and the other as a wet bulb temperature sensor. A very accurate psychrometer (Thies Guttingen range —10 °C to +50 °C) is placed very near the temperature duct. Some readings of dry bulb temperature and wet bulb temperature are taken for comparison. Two such temperature ducts are made.

The differential outputs of the dry bulb and wet bulb sensors are fed to the input of the differential amplifier circuit which is calibrated voltage to current wise.

3. Observations over bare soil

Observations were carried out on a bare plot at Central Agro-Meteorological Observatory, Pune (Lat. 18°32′N and Long. 73° 51′E) over some days in the month of February 1980.

The dry bulb temperature and wet bulb temperature differences $\triangle T$ and $\triangle T_w$ respectively were measured continuously over the same height interval between one metre and three metres a.g.l. The sensors were mounted on a small tower. The observations of ambient dry bulb temperature and wet bulb temperature were taken by measuring corresponding voltage output on digital voltmeter and then their values were obtained from respective calibrated graphs. The ambient values were taken at one metre level only for every 15 minutes. The continuous record of ambient values of temperature were not possible due to some technical difficulties.

The observations of net radiation fluxes were taken for every fifteen minutes interval of time for Funk type Net-Radiometer installed at 1.5 metre height from the ground and fifteen feet away from the tower for the same LAT hours. The net radiometer values are accurate within $\pm$ 3 % of the calibrated values. In the absence of measurement of soil heat flux the values of soil heat flux G obtained by Kelkar *et al.* (1980) in the month of February 1976, at the observatory were used in this study of same LAT hours. It is assumed the values of G are not significantly different.

4. Calculations of Bowen's ratio

From Eqn. (4) we have $\beta = \gamma \dfrac{\triangle T}{\Delta q}$, where $\gamma = 1{\cdot}02 \dfrac{C_p}{L}$ within $\pm$ 1 % over a very wide range.

TABLE 1

Surface pressure 950 mb, *Location* **: Central Agrometeorological Observatory, Pune**

Time (IST) Hr. & Min.	Temp. & sp. humidity at 1 m level a.g.l. Dry bulb T_1 °C	Wet bulb Tw_1 °C	Specific humidity q_1 (gm/kg)	3 m level a.g.l. Dry bulb T_2 °C ($T_1 - \triangle T$)	Wet bulb Tw_2 °C ($Tw - \triangle Tw$)	Specific humidity q_2 (gm/kg)	Diff. of Temp. & sp. humidity $\triangle T$ (°C)	$\triangle q$ (gm/kg)	β ($\times 10^{-4}$)	Latent heat of vaporization L_v (cal/gm)	Net radiation R_{Net} (cal/cm²/min) R_{Net}	Soil heat flux G in (cal/cm²/min) G	Mass flux E (gm/cm²/min) ($\times 10^{-4}$) E
15 February 1980													
1834	28.5	18.2	9.704	28.445	18.09	9.582	+0.055	+0.122	+1.898	581.255	—0.195	—0.075	—1.73
1934	27.2	20.5	13.326	27.123	20.39	13.203	+0.077	+0.123	+2.633	581.985	—0.183	—0.067	—1.574
2034	22.0	17.5	11.456	21.857	17.313	11.279	+0.143	+0.177	+3.381	584.92	—0.158	—0.065	—1.188
16 February 1980													
0949	20.5	14.7	8.736	20.412	14.601	8.723	+0.088	+0.013	+28.3	585.748	+0.648	+0.133	+3.107
1019	22.5	15.6	8.959	22.39	15.325	8.683	+0.11	+0.275	+1.674	584.631	+0.8	+0.16	+9.377
1104	23.4	15.2	8.128	23.345	15.123	8.06	+0.055	+0.068	+3.389	584.11	+0.8	+0.1916	+7.779
1119	23.4	15.2	8.128	23.345	15.123	8.06	+0.055	+0.068	+3.389	584.11	+0.792	+0.1916	+7.677
2019	20.6	15.0	9.112	20.38	14.78	8.875	+0.22	+0.237	+3.879	585.726	—0.147	—0.0666	—0.996
2049	21.5	14.9	8.557	21.214	14.724	8.474	+0.286	+0.083	+14.41	585.24	—0.147	—0.0666	—0.567
17 February 1980													
0819	11.6	9.5	7.267	11.446	9.434	7.303	+0.154	—0.036	—17.7	590.845	+0.387	+0.0817	—6.71
0834	16.5	12.1	7.565	16.335	11.968	7.515	+0.165	+0.05	+13.74	588.076	+0.387	+0.817	+2.187
0949	21.0	14.5	8.311	20.934	14.478	8.3119	+0.066	+0.0009	+306.6	585.458	+0.637	+0.33	+0.2719
1249	28.5	15.0	5.802	28.445	14.89	5 7	+0.055	+0.102	+2.27	581.255	+0.717	+0.1617	+7.786

$$\therefore \beta = 1 \cdot 02 \frac{C_p}{L} \frac{\triangle T}{\triangle q} \quad \text{Where } \triangle T = T_1 - T_2 \;\&\; \triangle q = q_1 - q_2$$

Where $\overline{L}$=mean of latent heats L_1 and L_2 at temperatures T_1 and T_2 respectively.

Let T_1, T_{w1} and T_2, T_{w2} be the dry bulb and wet bulb temperatures at one and three metres a.g.l. respectively (*see* Fig. 4). While $\triangle T$ is read directly from the chart record obtained by the instrument, Δq is calculated from recorded wet bulb and dry bulb temperatures at level one and the difference between two levels as given below :

$$L_1 (W'_1 - W_1) = C_p (T_1 - Tw_1)$$

$$\therefore W_1 = W_1' - C_p/L (T_1 - Tw_1) \times 1000 \text{ gm/kg}$$

TABLE 2

Mean value of mass flux (mm/hr)

Period (LAT)	Dates (Feb 1980)		
	15	16	17
Morning observation			
0800-0900	—	+0.224	—0.019
0900-1000	—	+0.309	+0.35
1000-1100	—	+0.61	+0.53
1100-1200	—	+0.49	+0.57
Evening observation			
1700-1800	—	—	—0.088
1800-1900	—0.117	—	—0.101
1900-2000	—0.11	—0.047	—

Location : Central Agro-Meteorological Observatory, Pune.

where, W_1 and W_1' are observed and saturated mixing ratios corresponding to temperatures T_1 and Tw_1 at surface pressure and

$$q_1 = \frac{W_1}{1000 + W_1} \times 1000 \text{ gm/kg}$$

Similarly $L_2 (W'_2 - W_2) = C_p (T_2 - Tw_2)$ and $W_2 = W'_2 - C_p/L (T_2 - Tw_2) \times 1000$ gm/kg.

Where, W_2 and W_2' are observed and saturated mixing ratios corresponding to temperatures T_2 and Tw_2 at surface pressure and

$$q_2 = \frac{W_2}{1000 + W_2} \times 1000 \text{ gm/kg}$$

Mixing ratios are expressed as gm/kg. From the value of q_1 and q_2, Δq is found.

5. Discussion of β and E (Bowen's & mass flux of water vapour

The Bowen's ratio values are found to be very small of the order of 3.2×10^{-4} to 28.0×10^{-4}. Therefore, L_E almost equal to (R_{Net} — G). Also Q_E is larger than Q_H. Therefore, the heat input from surface to the atmosphere is mainly in the latent form. It is the case of increased atmospheric humidity (Oke 1978). Very few values of β are negative.

The mass fluxes of water vapour E are found to be positive in the morning increasing from 8 to 12 hrs LAT. They are of the order of 0.0003 to 0.001 gm/cm²/min. It is the case of evaporation which indicates that E is away from the surface. The values of E are found to be negative in the evening hours as can be expected from condition for dew deposition in winter. It will be interesting to transform mass flux into surface evaporation and thereupon to compare the result with class A Pan observations.

The mean hourly value of observed surface evaporation is of the order of 0.357 mm/hr. The surface evaporation values are comparable with mean hourly winter values of the order of 0.300 to 0.4372 mm/hr of class A Pan observations for the same place (India Met. Dep. 1980). However, these observed values of surface evaporation are on the higher side compared to expected daily soil evaporation. The various measured and calculated parameters are tabulated in Tables 1-2 for dates 15, 16, 17 February 1980 respectively.

6. Conclusion

The instrument for measurement of Bowen's ratio using ventilated thermistors for temperature and humidity measurement was found to be quite suitable for carrying out the energy balance studies near to the surface. The instrument was tested for some days in winter season only.

From the calculations of fluxes of mass, mean hourly values of evaporation were found to be comparable with observed values of class A Pan but on the high side compared to soil evaporation values. The discrepancy may be reduced by a more suitable choice of heights near the ground than the levels used in this study.

Acknowledgements

Discussions with Shri B. Srinivasa Murthy, Meteorologist, Division of Agricultural Meteorology, Pune, have been very helpful in the preparation of the paper

The authors wish to express their thanks to Shri T. D. Pradhan and the staff of Central Agrometeorological Observatory, Pune for their cooperation during the experiment.

Thanks are also due to many colleagues in the I & OT Division for their help in numerous ways.

The authors wish to thank Dr. Bh. V. Ramana Murty, Director, Indian Institute of Tropical Meteorology for permission to publish this work.

References

Graeme, Tobey, Huelsman, 1971, '*Operational amplifier design and applications*', Mc Graw Hill Book Company, pp. 225-226.

India Met. Dep., 1980, 'Evaporation Data of observatories in India, 27 pp.

Kelkar, R.R. *et al.*, 1980, 'Observations of soil heat flux at Pune using a heat flux plate', *Mausam*, **31**, 1, pp. 151–156.

McNeil, David D. and Shuttleworth, 1975, Comparative Measurements of the Energy Fluxes Over a Pine Forest, *Boundary Layer Meteorology*, **9**, pp. 297–313.

Oke, T.R., 1978, '*Boundary Layer Climates*', Metbuen & Co. Ltd., A Halsted Press Book, John Wiley and Sons, New York, pp. 58-59.

Shwerdtfeger, Peter, 1976, *Development in Atmospheric Science*, **6**, 'Physical principles of micrometeorological measurements', Published by Eslsevier Scientific Publishing Company, Amsterdam, Oxford, New York, pp. 50-51.

Slatyer, R.O. and Mcllroy, I.C., 1961, '*Practical Microclimatology*, Commonwealth Scientific & Industrial Research Organisation, Australia, pp. 3–54, 3-55.

YSI precision thermistor, November 1976, Yellow Springs Instrument Co. Inc. Yellow Springs, Ohio 45387