551·573·524:633·11

A preliminary study of daytime evaporation in relation to variations of temperature, wind speed, zero-plane displacement and wind profile over a wheat crop at Poona

B. PADMANABHAMURTY

Meteorological Office, Poona

(*Received 23 August 1963*)

ABSTRACT. The paper summarises the results of wind, temperature and evapotranspiration observations taken over a wheat field at Poona. Daytime variations of zero-plane displacement, temperature and wind speed are presented. Their systematic variation during the day is also expressed mathematically. Comparison of evapotranspiration by Thornthwaite's original formula as modified by Rider and lysimetric values has been made. Better agreement could be obtained between lysimeter values and computed evapotranspiration both averaged over a ten-day period by abandoning the assumption of logarithmic variation of vapour pressure in Thornthwaite's formula and by employing the diurnal variation of zero-plane displacement.

1. Introduction

Of the various factors with which the agriculturist is concerned the return of moisture from natural land surfaces to the atmosphere occupies an important place. This transfer of moisture from vegetative surfaces comprises water losses from bare soil as well as transpiration from plants and is termed combinedly as evapotranspiration. Great interest has been evinced, of late, to measure this parameter as accurately as possible. Several techniques of measurement are in use and among them the aerodynamic method has been suggested to be applicable for short intervals of time. In connection with the estimation of evapotranspiration from a wheat field the author made an attempt to compute evapotranspiration from measurements of temperatures and wind speeds at three levels over the crop. The present paper embodies a preliminary analysis of wind, temperature as well as evapotranspiration observations.

Measurement of temperature has been made with Assmann Psychrometer while wind speeds were measured with Sheppard cup-type anemometers. The description of these is too well known to need any reproduction here. The integrated hourly wind speed can be known by noting the successive dial readings and reading from the calibration graphs supplied by the manufacturer. The wind instruments were tested in a wind-tunnel for any change in their calibration before installation. From wind observations at three levels, zero-plane displacement has been evaluated assuming logarithmic profile equation for wind speed at three levels.

2. Analysis of Wind

Let z_1, z_2, and z_3 be the three heights measured from the ground surface and let the winds determined be u_1, u_2 and u_3. Then the distance d (known as the zero-plane displacement) may be obtained from the equation (Deacon 1949, 1953)—

$$(u_2-u_1)/(u_3-u_2) = \ln\frac{z_2-d}{z_1-d}\Big/\ln\frac{z_3-d}{z_2-d}$$

d is best determined graphically for a given set of z values, *i.e.*, by preparing a graph of

$$\ln\frac{z_2-d}{z_1-d}\Big/\ln\frac{z_3-d}{z_2-d}$$

against d for a range of arbitrary values of d, and then, from some measurements of $(u_2-u_1)/(u_3-u_2)$ the appropriate value of d can be read. The concept of "zero-plane displacement" originally due to Thornthwaite implies that the logarithmic law applies only above the level where active turbulence begins. This level rather than the ground level is the base of reference for the wind velocity profile and is designated by Thornthwaite as the source surface for turbulent transfer. It is realised that if the crop is growing, d will change with crop height (Calder 1949) as it is liable also to do with varying wind strength.

The equation for vertical flux of water vapour through the atmosphere can be written as—

$$E = -\rho K \frac{\partial q}{\partial z} \qquad (1)$$

where E is flux of water vapour/unit area/unit time, ρ air density, K is coefficient of eddy diffusivity, q specific humidity and z is height measured vertically upwards. Under assumption of logarithmic profile of wind, as observed in wind-tunnel experiments we have

$$K = k^2 z^2 \cdot \frac{\partial u}{\partial z} \qquad (2)$$

Extending the analogy to crop fields only with the idea of zero-plane displacement (Thornthwaite and Holzman 1942, Pasquill 1949a) we have

$$K = k^2 (z-d)^2 \frac{\partial u}{\partial (z-d)} \qquad (2a)$$

where k = von Kármán's constant $(0\cdot4)$ (Priestley 1959)

z = height above ground level

d = zero-plane displacement and

u = wind speed

Equation (2a) can be written as

$$K = k^2 (z-d) \frac{\partial u}{\partial [\ln(z-d)]} \qquad (3)$$

$$= k^2 (z-d) \times A$$

where

$$A = \frac{\partial u}{\partial [\ln(z-d)]} \qquad (4)$$

i.e., A is the slope of velocity profile along the vertical when the vertical is represented by $\ln(z-d)$. In other words, it is assumed that if at any time, velocity is plotted against $\log_e$ (height), the curve is a straight line with slope A, provided that the height is measured not from the ground surface but from a level d units above the ground surface. A and d are both functions of time of the day and crop height. Their variation during daytime is studied with the help of observed values of u at three levels; the levels being 120, 185 and 250 cm above ground. The crop height at this time was 110 cm above ground.

Preliminary analysis showed that each day's observations taken separately did not show much of regularity in the variation of d and A. It was, therefore, decided to find averages for a period during which the crop height and meteorological conditions were reasonably uniform. During this period (31 January to 9 February 1963) the wind was mainly easterly attaining a maximum value in the afternoon. The sky was practically clear during these days and the moisture status of the air was more or less the same every day. The crop was at a mature stage and showed no variation during the period; the average height being 110 cm. d and A were determined for each hourly set of wind observations from 0800 to 1800 IST on each of the ten days under study. The mean of the ten-day period was found for each hour. d and A were found to show a systematic variation with the advance of the day. The variation is shown in Figs. 1 and 2. The curves shown in these figures are the parabolas fitted to the computed values of d and A, by the usual method of least squares (Conrad 1950). From equation 4 we get—

$$\frac{\partial u}{\partial (z-d)} = \frac{A}{(z-d)} \qquad (5)$$

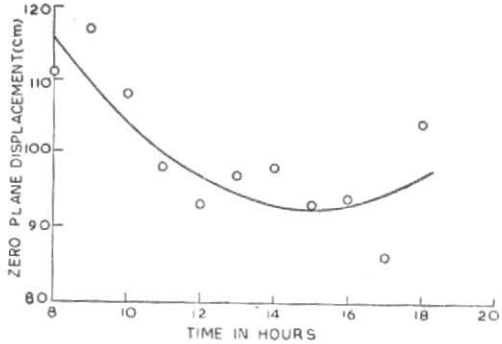

Fig. 1. Zero-plane displacement

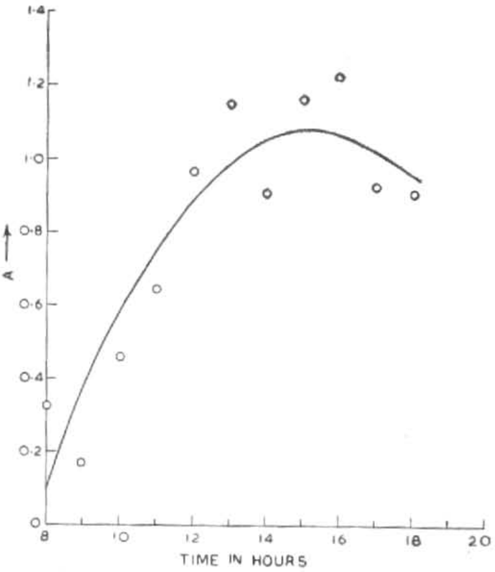

Fig. 2. Day-time variation of 'A'

Thus $A/(z-d)$ gives the vertical variation of u at level z. Hourly values of $\partial u/\partial(z-d)$ were calculated for the intermediate level (185 cm) of wind observation taking $z=z_2$ and picking the values of A and d from Figs. 1 and 2. The hourly variation of $A/(z_2-d)$ is shown in Fig. 3. According to the very assumption of logarithmic profile, it is, of course implied that the wind increases with height. Fig. 3, however, highlights that this increase of wind with height is most intense at about 1500 IST being about 10 times its magnitude in the morning.

Figs. 4 and 5 show the daytime variations of dry bulb temperature and wind velocity at z_2 (185 cm), averaged over the 10-day period. Both the temperature and wind velocity attain their maximum value at about 1500 IST.

The hourly values of A, d, T and u plotted against time could be fitted to the following parabolic equations—

$$A = -\cdot 0185\, t^2 + \cdot 3052\, t - \cdot 1779 \quad (6)$$

$$u = -\cdot 0439\, t^2 + \cdot 6917\, t - \cdot 4709 \quad (7)$$

$$T = -\cdot 3598\, t^2 + 5\cdot 5904\, t + 10\cdot 2791 \quad (8)$$

$$d = \cdot 4348\, t^2 - 7\cdot 6853\, t + 123\cdot 629 \quad (9)$$

where the symbols signify as before except that T is the temperature and t is time in hours beginning with $t = 0$ at 0800 IST.

3. Computation of Evaporation

In the application of Thornthwaite and Holzman (1939) aerodynamic formula as modified by Pasquill (1949a) for evaporation

$$E = \frac{\rho k^2\,(u_2-u_1)\,(q_1-q_2)}{\left[\log \frac{(z_2-d)}{(z_1-d)}\right]^2}\,, \quad (10)$$

it is customary to use (Rider 1957) one value of d for a day, determined from a set of wind observations on that day at hours when the vertical stratification of air is neutral. Pasquill (1949b) has stated that if the average value of d is determined for a day for all the wind observations throughout the day without referring to vertical stratification, then the formula (10) is likely to underestimate the evaporation to the extent of about 10 per cent,

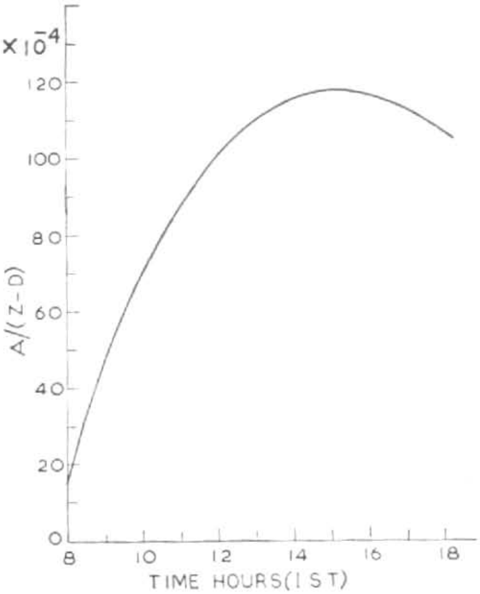

Fig. 3. Daytime variation of $A/(z-d)$

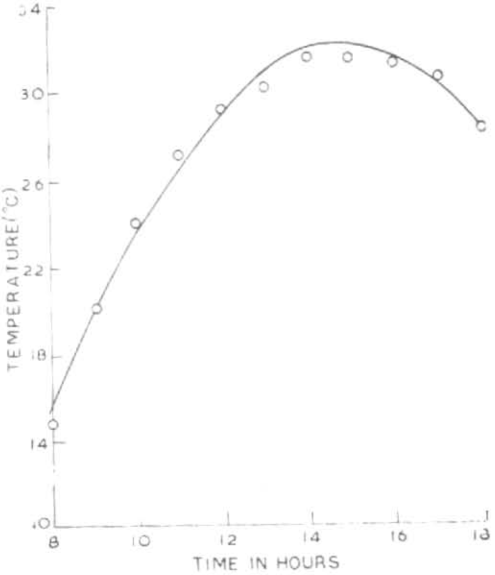

Fig. 4. Temperature at the middle level

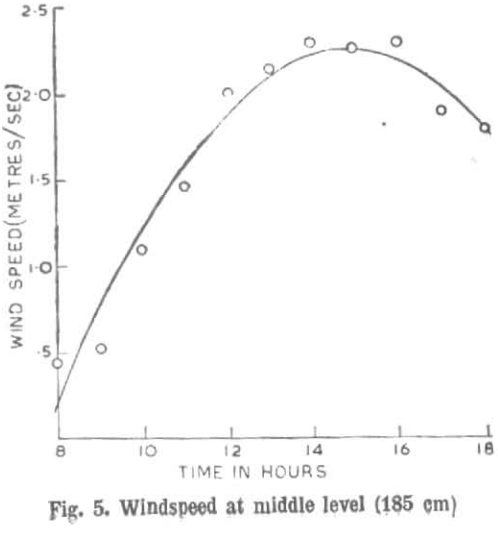

Fig. 5. Windspeed at middle level (185 cm)

TABLE 1

Evapotranspiration in gm/cm² in 12 hours from 6 A.M. to 6 P.M. at Agrimet. Observatory, Poona

Date	Computed from Thornthwaite's formula(10)	Measured by Lysimeter
31-1-1963	0·0865	0·1890
1-2-1963	0·0275	0·1513
2-2-1963	0·0845	0·1379
3-2-1963	0·1151	0·1753
4-2-1963	0·0804	0·1498
5-2-1963	0·0696	0·1127
6-2-1963	0·0928	0·1009
7-2-1963	0·0491	0·1009
8-2-1963	0·0306	0·0708
9-2-1963	0·0169	0·0438

Assuming the logarithmic profile for wind at all hours, d was calculated from wind observations at three levels for each hour separately and the mean value of d for the day was obtained. This value of d was adopted for the day for subsequent calculations. To facilitate the computation of d from the wind observations of each hour a nomogram was prepared.

Water losses were calculated from the formula—

$$E = \frac{3\cdot46\times10^{-5}(u_2-u_1)\ (e_1-e_2)}{T\left\{\log_e \dfrac{z_2-d}{z_1-d}\right\}^2}\times 3600 \qquad (11)$$

where E is evaporation in gm/cm²/hr, u is measured in cm/sec, e is actual vapour pressure in mb, z and d in cm and T in degrees Absolute. This is only a convenient form of the above original formula (10). E is calculated for each hour from 8 A.M. to 6 P.M. The hourly values are added to get the water loss for the 10-hour period 8 A.M. to 6 P.M. in gm/cm²/each day. These values are shown in col. 2 of Table 1. During these winter days preliminary tests showed almost negligible evapotranspiration from lysimeters between 6 A.M. to 8 A.M.

Lysimeters are containers big enough to allow the plants grow as freely as in the field. The container (approx. 1 metre cube) was supported on a weighing machine capable of handling large weights (1 ton). The weighing machine was placed inside another tank of a slightly bigger capacity which was sunk into the middle of a field where a crop of the same variety (in this case wheat) was grown in such a way that the level of the soil in the inner tank (*i.e.*, tank containing the plants) was the same as that in field. To simulate field conditions, care was taken to see that the soil profile, the date of planting, seed rate, dates of irrigation, dose of manure, other cultural operations etc with respect to the plants grown in the tanks were kept exactly the same as those observed with regard to the plants grown in the field. The soil of the experimental tank was raised to field capacity on days when the crop in the field was irrigated. Proper drainage system was also provided to ensure drainage of overflowing water when heavy showers occur. Periodical growth observations of the plants in the tanks and of those in the field were taken to check up whether the plants in the tanks were growing as freely as those in the field.

Lysimeter readings are taken at 6 A.M. and 6 P.M. The difference between the two gives the measured water loss. The value of water loss in gm/cm² for the 12-hr period is shown in col. 3 of Table 1. It will be seen that on every day, the calculated water loss was much less than the measured water loss, being almost half of the measured one. Possible causes of this large difference were examined.

(*i*) *Inaccuracy of observations*—It can be argued that inaccuracy of observations may

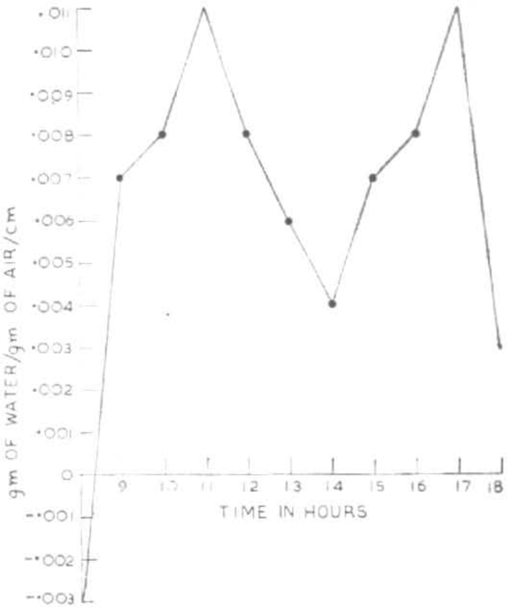

Fig. 6. Daytime variation of $\partial q/\partial z$

be reflected in the observed anomalies but consistently too low values of calculated water losses could not, however, be completely attributed to instrumental errors.

(*ii*) *Inadequacy of fetch*—Could it be that the gradients of *e* which are measured with the equipment are not representative of the crop growing on the lysimeter due to inadequacy of the fetch ? The wheat crop over which the experiment was conducted extended about 80 metres towards the east and about that much towards the west but only 15 to 20 metres towards the north and south. During the period from 31 January to 9 February, the winds as judged fom P.T. anemograms were generally light and variable but on a few days these were steady easterlies. On examination of vertical vapour pressure profiles, it was clear that the profiles on these days were much more reasonable than on many other days suggesting that inadequate fetch was responsible for part of the discrepancy.

(*iii*) *Lapse rate*— Most of the time during the day when the experiment was in progress, unstable conditions prevailed. It has been known for long that Thornthwaite's formula which is derived for neutral conditions of the atmosphere underestimates water losses when unstable lapse rates prevail. In middle latitudes, the underestimation is known to be of the order of 10 to 15 per cent. It is perhaps possible that in tropical latitudes where heat supply is plentiful, the underestimation due to the prevailing unstable conditions is as much as 40 to 50 per cent. At this stage of experimentation this can only be a conjecture which, however, requires further investigation.

(*iv*) *Logarithmic profile for vapour pressure*— As stated earlier Thornthwaite's formula is based on the assumption of logarithmic law both for wind and specific humidity. For all practical purposes, the logarithmic law for specific humidity implies the logarithmic law for vapour pressure of which vertical profiles are prepared. How will the computations be affected if this logarithmic assumption for vapour pressure is abandoned and instead the vapour pressure gradient from our vertical profile of the vapour pressure is computed ?

From equations (1) and (2a), assuming logarithmic profile for wind only, we get

$$E=-\rho\left\{k^2(z-d)^2\frac{\partial u}{\partial(z-d)}\right\}\frac{\partial q}{\partial z} \qquad (12)$$

$$=-\rho k^2\left\{\frac{\partial u}{\partial \ln(z-d)}\right\}(z-d)\,\partial q/\partial z$$

Or, from equation (4)

$$E=-\rho k^2 A(z-d)\,\partial q/\partial z \qquad (13)$$

$\partial q/\partial z$ at level z_2 was found every hour starting from 8 A.M. to 6 P.M. from 31 January to 9 February 1963, and the average hourly values over the ten-day period were obtained. These are shown in Fig. 6. Values of d and A were taken from computed averages respectively and the value of von Kármán's constant was taken as $0\cdot4$. Hourly values of evaporation were then calculated employing equation (13). It was found that the daily evapotranspiration came out to be $0\cdot1157$ gm/cm². Mean daily value of evapotranspiration obtained from lysimeters over these ten days is $\cdot1173$ gm/cm². The estimated value of evapotranspiration now came very close to the measured one. This may be just a fortuitous occurrence and should be tested with more observations. But, if it is confirmed, it would constitute a valuable result.

4. Conclusions

1. Averaged over a ten-day period under conditions described in this experiment hourly values of d, A, u and T plotted against time can be well represented by the following equations of parabolas—

$$d=\cdot4348\,t^2-7\cdot6853\,t+123\cdot629$$

$$A=-\cdot0185\,t^2+\cdot3052\,t-\cdot1779$$

$$u=-\cdot0439\,t^2+\cdot6917\,t-\cdot4709$$

$$T=-\cdot3598\,t^2+5\cdot5904\,t+10\cdot2791$$

where t = time in hours beginning with $t=0$ at 0800 IST. A, u and T attain maximum values and d attains minimum at about 1500 IST.

2. Vertical increase of wind with height at maximum temperature epoch is found to be 10 times as large as it is in the morning.

3. Thornthwaite's formula as modified by Rider when applied with the average value of d gave computed evaporation which was only about half of that measured by lysimeter. But when the hourly values of A, d and $\partial q/\partial z$ averaged over ten-day period mentioned earlier were introduced in the computation and assumption of logarithmic variation of vapour pressure was abandoned, the computed value agreed closely with the measured value. This particular result is very interesting, but it is necessary to confirm it by further extensive work.

5. Acknowledgements

The author is thankful to Sarvashri M. Gangopadhyaya, Director, Agricultural Meteorology, P.S. Hariharan and G.C. Asnani, Meteorologists, for their constructive criticism at every stage of the work and providing facilities to carry out these experiments. Thanks are also due to Shri S. Venkataraman with whose help the direct measurement of evapotranspiration by the gravimetric method was made.

REFERENCES

Calder, K. L.	1949	*Quart. J. Mech.*, **2**, Pt. 2, p. 153.
Conrad, V. and Pollak, L. W.	1950	*Methods in Climatology*, Harvard Univ. Press.
Deacon, E. L.	1949	*Quart. J.R. met. Soc.*, **75**, p. 89.
	1953	*Geophys. Mem., London*, 91.
Pasquill, F.	1949a	*Proc. roy. Soc.*, A, **198**, p. 116.
	1949b	*Quart. J.R. met. Soc.*, **75**, p. 249.
Priestley, C. H. B.	1959	*Turbulent transfer in the lower atmosphere*, The Univ. of Chicago Press.
Rider, N. E.	1957	*Quart. J.R. met. Soc.*, **83**, p. 181.
Thornthwaite, C. W. and Holzman, B.	1939	*Mon. Weath. Rev. Wash.*, **67**, p. 4.
	1942	*Tech. Bull. U.S. Dep. Agric.*, 817, p. 23.