that water is available freely to the plant roots. Over the period during which the measurements of Fig. 4 were made this was certainly not the case.

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List of references

Aitchison, G. D. and J. W. Holmes : *Aust. J. Appl. Sci.* 4 (1953) 260–273.

Bavel, C. H. M. van, E. E. Hood and N. Underwood : *Trans. Amer. Geophys. Union* 35 (1954) 595–600.

Belcher, D. J., T. R. Cuykendall and H. S. Sack : *C.A.A., U.S.A. Tech. Development Rep.* No. 127 (1950).

Gardner, W. and D. Kirkham : *Soil Sci.* 73 (1952) 391–401.

Guéron, J. : *J. Phys. Radium* 15 (1954) 65A–75A.

Knight, A. H. and T. W. Wright : *Radioisotope Conference, Oxford* (1954) Vol. II, pp. 111–122.

Penman, H. L. : *Rep. of the 13th Int. Horticultural Congress* (1952) 1–12.

Sharpe, J. : *Brit. J. Appl. Phys.* 4 (1953) 93–94.

Spinks, J. W. T., D. A. Lane and B. B. Torchinsky : *Can. J. Technology* 29 (1951) 371–374

Wallace, P. R. : *Nucleonics* 4 (2) (1949) 30–55.

EVAPORATION AT NIGHT

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Summary

Direct measurements of evaporation from a short grass surface are compared with humidity gradients in the grass. At night, when the air in the cover is unsaturated, evaporation takes place by the diffusion of water vapour from the soil surface through a thin layer of air in which the transfer coefficient is seldom greater than twice the molecular value. The rate of evaporation is of the order of 1 μg cm^{-2} sec^{-1}, or 0.04 mm/hr.

1 Little attention has been paid to evaporation from soil and from vegetation during the hours of darkness. It has generally been assumed that when weather conditions favour an upward rather than a downward movement of water vapour at night, evaporation rates are negligible compared with those which prevail during the day and this view has strong biological and physical support. It is believed that in most species stomatal closure at sunset is sufficiently complete to make transpiration impossible. Even in the absence of a mechanical barrier, no plant could transpire into an atmosphere which had been brought to saturation by nocturnal cooling. Furthermore, evaporation requires energy, and since in temperate latitudes at least the earth's surface always *loses* radiant energy at night, whether the sky be clear or clouded, it might be argued that other heat transfer processes would tend to *supply* heat to the radiating surfaces, e.g. by condensation, rather than to remove it by evaporation. Nevertheless, such observations as have previously been made of water-vapour fluxes after dark (e.g. by Pasquill, 1949, Rider, 1954, and Swinbank, 1955) suggest that slight evaporation may occur after sunset in suitable

conditions. This paper presents measurements of such evaporation from a short grass surface with evidence that an explanation is to be sought in diffusion of water vapour from the soil surface rather than in some anomalous behaviour of the plant.

2 The observations to be described were obtained in the course of an investigation on dew formation carried out in a cricket field in the autumn of 1953. The apparatus consisted of a dew balance (JENNINGS and MONTEITH, 1954) giving a continuous record of the weight of a naturally exposed block of turf and soil, 25 cm deep and 330 cm^2 in area, which had been separated from the parent material without disturbing the original structure. Both thermally and in appearance the test surface was indistinguishable from its natural surroundings. The record obtained had a sensitivity of about 2 mg cm^{-2} per cm record against a time scale of 0.5 ha per cm record and the mean rate of evaporation over a ten minute period could generally be estimated with an accuracy of 5 per cent.

Temperatures at the surface of the soil and 1 cm above it were measured by thermocouples (38 s.w.g. copper-constantan) and a third junction wrapped with an adequate length of cotton thread gave the wet-bulb temperature and hence the absolute humidity of the air at 1 cm. SHEPPARD cup anemometers gave wind speeds at four heights between 25 and 200 cm. Observations were made every quarter, half, or whole hour depending on the rate at which conditions were changing, and each run, which lasted for ten minutes, consisted of ten galvanometer readings (later meaned) for each thermocouple, and the mean wind speed for the interval.

Throughout the period of the observations, the grass was kept short by twice-weekly mowing and the average blade height was about 1 cm. Rainfall in the period was 19 mm between August 29 and September 2, 13 mm on September 17, and 23 mm between September 20 and 24.

3 A preliminary inspection of the records showed that evaporation at night occurred only when the air in the grass cover was unsaturated. During sunshine, the relative humidity in the cover was surprisingly low. For example, at 15.00 h September 7, with a wind speed at 25 cm of 2 m/sec and an evaporation rate of 10 μg cm^{-2} sec^{-1} the relative humidity was only 53 per cent.

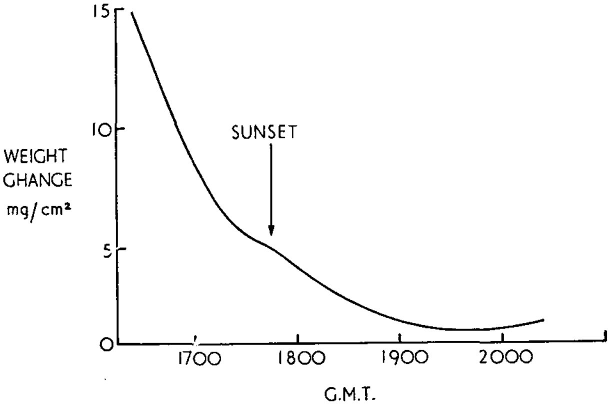

FIG. 1. EVAPORATION ON THE EVENING OF 28 SEPTEMBER, 1953.

Towards sunset, when the sky was clear and the wind at screen level was less than 2 m/sec, the temperature within the grass fell much more rapidly than the dew-point, and within an hour or two of sunset the air became saturated with condensation appearing on the leaves. When, on account of cloud cover or of an unusually high wind (greater than 2 m/sec), cooling was slow, saturation was approached less rapidly and sometimes not reached in the course of the night. A number of the records showed a sudden decrease in evaporation occurring shortly before sunset which is thought to have been caused by stomatal closure, and an example of this is given in Fig. 1, the record for September 28, when sunset was at 17.50 h. Between 17.15 and 17.30 evaporation decreased by a factor of three to 0.8 μg cm^{-2} sec^{-1} but did not become zero until 19.30 h.

If this evaporation were to be attributed to leakage through incompletely closed stomata, or through other permeable parts of the leaves, a correlation might be expected between the rate of evaporation and the vapour pressure difference between the interiors of the leaves and the air around them. Assuming the temperature T of the air was not significantly different from that of the leaves, the required vapour pressure difference becomes the difference between e_S (T), the vapour pressure of the saturated air within the leaf, and e, the vapour pressure of the air. When the evaporation E was plotted against e_S $(T)-e$ for eighteen observations covering five different nights, a remarkably linear relationship was obtained for three of the nights, and for two of these the points lay on the same straight line. On the remaining two nights, however, moisture had been observed on the grass at the same time as evaporation was recorded by the balance, and for these nights the evaporation was anomalously high.

Simultaneous condensation on the leaves and evaporation from the grass cover as a whole is inexplicable in terms of transpiration. An alternative hypothesis is the upward diffusion of water vapour from the surface of the soil

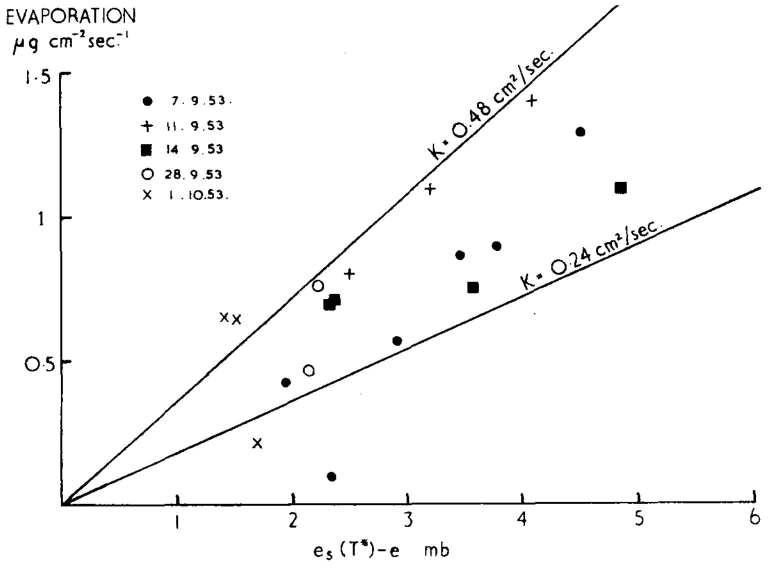

FIG. 2. RELATIONSHIP BETWEEN EVAPORATION RATE AND VAPOUR PRESSURE GRADIENT IN GRASS COVER.

produced by a suitable humidity gradient. When the leaf surfaces were warmer than the dew point of the surrounding air, the whole of this vapour stream would escape to the atmosphere, but when the leaves cooled to the dew-point, part would be trapped by condensation. Following this assumption, E may be plotted against the vapour pressure difference between the soil and the air at 1 cm. The healthy state of the grass was an indication that the soil atmosphere was virtually saturated at the level of the roots, and assuming the relative humidity of the surface soil was equally high, the required difference becomes $e_s\,(T^*)-e$, where T^* is the surface temperature.

Fig. 2 shows how the observations appear when plotted in this way. The ratio of evaporation to humidity gradient, expressed in g cm^{-4}, is the apparent diffusion coefficient K (cm^2/sec), and with four exceptions the points lie between $K = 0.24$ cm^2/sec, the molecular value of the coefficient, and 0.48 cm^2/sec. The two points for which $K < 0.24$ were occasions when considerable moisture had appeared on the leaves, and it is probable that an appreciable fraction of the vapour leaving the surface was intercepted before it escaped to the atmosphere. This would lead to underestimation of E and hence of K. On the whole, however, the anomalous points obtained on an $e_s\,(T)-e$ diagram disappear when T^* is substituted for T, supporting the hypothesis of diffusion from the soil and suggesting that, on the majority of occasions shown, an negligible amount of the evaporation from the soil was condensed on the leaves. The scatter of points is probably partly experimental and partly real. It was impossible to leave the surface thermocouple in position from one night to another, and in view of the well known difficulty in measuring surface temperature, there can be no guarantee that all the observations were equally representative of this quantity. Cutting the grass may have significantly affected the aerodynamic characteristics of the cover, and hence the transfer coefficient within it, but it is noteworthy that on any one night K appears to have been independent of wind speed. For example, on September 11 17.30 h the wind speed at 25 cm was 1.78 m/sec, and 19.30 h, 2.93 m/sec. Corresponding values of K were 0.48 and 0.43 cm^2/sec.

4 The close approach of the transfer coefficient to the molecular value and its independence of the wind speed at the higher levels suggest the existence of a non-turbulent layer of air within the grass cover. It is, therefore, interesting to compare the observed wind profiles in conditions of neutral stability with the theoretical formulae for aerodynamically smooth flow:

$$u = \frac{u_*}{h} \ln \frac{9.05\, u_* z}{\gamma} \tag{1}$$

and for fully rough flow

$$u = \frac{u_*}{h} \ln \frac{z}{z_0} \tag{2}$$

where u_*, the friction velocity, is proportional to the square root of the shearing stress, γ is the kinematic viscosity, z_0 is the roughness parameter and u is the velocity at height z cm ($10 < z < 10^3$). (See e.g. Deacon, 1954). The logarithmic profile indicated by both these formulae was obtained precisely on September 11 between 17.30 h and 21.30 h when there was little thermal stratification and the mean wind speed at 1 m was 3 m/sec. Application of Eq. 1 gave two inconsistent values of u_*, while Eq. 2 gave $u_* = 16$ cm/sec and $z_0 = 0.1$ cm – reasonable figures consistent with results obtained by other workers. It appears therefore that fully turbulent flow above short grass cover may not be inconsistent with a transfer coefficient *within* the cover of less than twice the molecular value.

5 Assuming that the range of transfer coefficients found at night was typical of daytime values also, it is possible to estimate roughly how much of the daytime evaporation took place directly from the soil surface and how much by transpiration through the leaves. An overestimate of the vapour pressure difference between the soil and the air is obtained by assuming the surface soil remained saturated during the day. On this basis the vapour pressure gradient on September 7 15.00 h was 15.2 mb/cm and with $K = 0.3$ cm^2/sec (the mean value for 18.30 h to 20.00 h the same day), a maximum estimate for evaporation from the soil is 3.7 μg cm^{-2} sec^{-1}. As the observed evaporation was 10 μg cm^{-2} sec^{-1}, the contribution of the grass may have exceeded 6 μg cm^{-2} sec^{-1}. The picture here is of an idealised cover in which the soil evaporates into a quasi-laminar layer about 1 cm deep while the grass transpires from a length of 1 cm into the turbulent airstream above it.

6 Nocturnal evaporation of the magnitude indicated in Fig. 1 and 2 may not be peculiar to short grass. It will certainly occur wherever cold radiating leaf surfaces are found within a few centimetres of a relatively warm soil surface, and even with taller crops where temperature and humidity gradients are smaller, greater mixing of the air within the crop may produce fluxes of the same order as those reported here. It is most unlikely, however, that nocturnal evaporation from any type of vegetative cover could ever be significant in comparison with transpiration rates prevailing during the day.

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REFERENCES

DEACON, E. L. : Vertical Profiles of Mean Wind in the Surface Layers of the Atmosphere. Meteorological Office, London. *Geophysical Memoirs*, No. 91 (1953).

JENNINGS, E. G. & J. L. MONTEITH : A Sensitive Dew-Balance. *Q. J. Roy. Met. Soc.* 80 (1954) 222–226.

PASQUILL, F. : Some Estimates of the Amount and Diurnal Variation of Evaporation from a Clayland Pasture. *Q. J. Roy. Met. Soc.* 75 (1949) 249–256.

RIDER, N. E. : Eddy Diffusion of Water Vapour and Heat near the Ground. *Phil. Trans. Roy. Soc.*, A, 246 (1954) 481–501.

SWINBANK, W. : Eddy Transports in the Lower Atmosphere. *Division of Meteorological Physics, C.S.I.R.O. Technical Paper* No. 2 (1955).