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**SUMMARY**

Arguments are presented suggesting that the difference between predicted interception loss given by the multi-layer MANTA model and the single source Rutter model, reported by Sellers and Lockwood (1981), are primarily related to differences in the treatment of aerodynamic transfer in saturated conditions. The reinterpretation is important in that, assuming the treatment used in the MANTA model is correct, changes in effective source position generate an unexpectedly large change in effective aerodynamic resistance. Attention is also drawn to features present in results given by the MANTA model operating in dry conditions which require further investigation.

1. **INTRODUCTION**

Sellers and Lockwood (1981) have described a comprehensive model (the MANTA model) of evaporation which incorporates an extension of the Rutter model of evaporation of intercepted rainfall (Rutter *et al.* 1971) to include a multi-level canopy. The greater realism of allowing different rates of evaporation and states of canopy wetness at various heights within the canopy gives increased insight into the process of evaporation and potentially more accurate predictions of evaporation, and the authors are to be congratulated on this step forward.

An important conclusion of their paper is that, when compared with the predictions of interception loss given by the Rutter model, the MANTA model predicts 20% more evaporation of intercepted water. Sellers and Lockwood consider that this difference is most likely attributable to the different treatments of the partially wet canopy in the two models, in particular the hysteresis effect present in the MANTA model. We would suggest that, although the different treatment of the partially wet canopy may make some contribution, this is not responsible for the major part of the difference, but rather that this is primarily related to differences in the rate of evaporation in totally wet conditions. This is significant in that it indicates where any proposed intercomparison between the two models, in a calibration against real data, might concentrate attention. From the point of view of practical application, using the simpler predictive models proposed by Rutter *et al.* (1971) and Gash (1979), it is important to establish whether the significantly enhanced evaporation rate does in fact occur as the effective source of water vapour rises in totally wet conditions, or whether it is an artefact of the way the aerodynamics are treated in the MANTA model. If it does occur, it will be necessary to quantify the reduction in the effective aerodynamic resistance used in these simpler models.

2. **WET CANOPY EVAPORATION**

The postulate we present is that the 20% difference in predicted total interception loss given by the Rutter model and the MANTA model, shown by Sellers and Lockwood (1981), hereafter called SL, is primarily related to the different rates of evaporation in totally wet conditions. For the purposes of developing the argument we adopt the simple one-off model of rainstorms proposed by Gash (1979). In short or low intensity showers e.g. Fig. 7 (SL, 1981) where canopy saturation is not achieved, the drainage predicted by both the Rutter and MANTA models (and observed in practice) is small, and the total interception loss is $(1 - p)$ times the total precipitation, where $p$ is the direct throughfall proportion. (We assume that in SL the MANTA and the Rutter model use the same, though unspecified canopy structure parameters). The interception loss for small storms is therefore largely model independent.

In more common high intensity storms, the model proposed by Gash (1979) envisages an individual rainstorm event as comprising a period of wetting up, a period of saturation (or supersaturation), and a period of drying out, with the canopy having a sufficient time to dry out before the next storm. Gash (1979) uses this simple one-off model to estimate the evaporation while wetting up the canopy, using an analytic integration of Rutter's partially wet description. Since the mean
rate of rainfall is generally about five times greater than the mean rate of evaporation, this period is usually of short duration and represents a small component (~ 5%) of interception loss. The MANTA model predicts an enhanced rate of evaporation during the wetting up period of a high intensity rainstorm (SL, Fig. 8), but if the saturated canopy evaporation rates in the two models were the same, it is unlikely that this could contribute more than a few per cent to the reported difference between the two.

Drainage rates decrease very quickly after rain has ceased and neither the Rutter nor the MANTA model, which use essentially the same formalism for drainage rate, predict a large drainage during an extended drying out period. It then follows that the description of the drying out of the canopy (considering only interception loss) is unimportant: the water in the canopy store will evaporate, and the total interception loss after rain ceases will equal, S, the canopy store. Some differences could occur if drying rates were very different, either as a result of small drainage differences in the two models, or in the event of a subsequent storm prior to complete drying. In fact, as Sellers and Lockwood point out, when considering the whole canopy behaviour, the drying response of both models is very similar; and the similarity in Figs. 8 and 11 of SL would be more obvious were the limiting rates of evaporation in (super) saturated canopy conditions the same in both cases. The apparent success of the Rutter hypothesis (Eq. (1) in SL) in describing the whole canopy behaviour in drying conditions is perhaps not surprising, since it has already had some success in this role. Shuttleworth (1978) applied the same physical principles used in SL within a single source framework, to demonstrate that it was possible to establish a relationship between the entity (C/S), defined in SL, and the effective canopy resistance as measured by micrometeorological experiment. Applying the Rutter hypothesis in drying conditions generated a variation in effective canopy resistance consistent with that observed in the field. It is interesting and relevant here to note that, in doing this, Shuttleworth (1978) deduced the relationship between \( \frac{W}{d} \) and \( \frac{C}{S} \) which is implicit in the Rutter hypothesis when applied in a single source canopy model. This relationship (Eq. (43) in Shuttleworth (1978) can be rewritten in simpler form (Eq. (65) and (66) in Shuttleworth (1978)) as

\[
W = \begin{cases} 
1 & \text{if } C \geq S \\
\frac{(R - 1)}{R - (S/C)} & \text{if } C < S
\end{cases}
\]

where \( R = \frac{r_{ST}}{r_a} (r_a - r_b) \left\{ \left[ \frac{\Delta}{\gamma} + 1 \right] r_b \right\} \)

(1)

(2)

Returning to our main line of argument, it is clear that, if the interception loss from small storms is model independent; if wetting up differences in high intensity storms are small; and if the predicted behaviour in drying out conditions are unimportant, and in any case similar; then the origin of the difference in predicted interception loss given by the Rutter and the MANTA models must be in the treatment of the evaporation during saturated conditions. This conclusion is supported by Fig. 8 in SL, where the evaporation rate given by the MANTA model during saturated conditions is about 20% bigger than that given by the Rutter model. Rutter and Morton (1977) have reported that their model is sensitive to the values of roughness length, \( z_0 \), and zero plane displacement, \( d \), used to derive the aerodynamic resistance; and a similar conclusion was drawn by Gash et al. (1980), who carried out a sensitivity analysis on the predicted mean evaporation rate during saturated conditions. It seems clear that, in application, the primary difference between the two models lies in their different aerodynamic assumptions in totally wet conditions.

Experimental evidence regarding the effective aerodynamic resistance to be used in the Rutter model is not conclusive. Calder (1977) deduced \( r_a \) as a free parameter in an optimization between the Rutter model and experimental data. He reported on a value around 3.5 s m\(^{-1}\) when assuming \( r_a \) was constant, and values of \( b \) in the order 14 to 21 when assuming the form \( (r_a = b/u) \), which values compare with an estimate of 16 based on canopy characteristics using the Rutter prescription. In an extensive series of experimental tests of the Rutter model at several forest sites Gash and Morton (1978), Gash et al. (1980), report general agreement between measurements of interception and predictions based on the Rutter model, but differences range between 14% and 21%.

In fact, because of the form used for the relationship between proportional wetted area and
the variable (C/S) shown in Fig. 1, and in particular because of the assumption that \( W = 0.8 \) at saturation, the difference between the effective aerodynamic resistance used in the Rutter and MANTA models is very marked. An estimate of the effective aerodynamic resistance used in the MANTA model, \( r^M_a \), is given by solving the equation

\[
0.8 \left| \frac{\Delta A + \rho c_p D/r^M_a}{\Delta + \gamma} \right| = 1.22 \left| \frac{\Delta A + \rho c_p D/r_a}{\Delta + \gamma} \right|
\]

where \( A \) is the total available energy, and \( r_a \) is the aerodynamic resistance used in the Rutter model.

For the conditions used in Figs. 8 and 10 of SL, Eq. (3) would imply \( r^M_a = 0.66 r_a \). The hypothetical meteorological conditions used in these figures are a little unusual (since \( A \sim 0 \)), and tend to emphasize model differences, but a change in aerodynamic resistance of this size in response to changing source height, is unexpected and requires investigation.

3. Dry Canopy Evaporation

Of equal importance is the result implicit in Fig. 12 of SL regarding behaviour in dry conditions, on which the authors make no comment. There is some uncertainty as to what is meant by a Rutter model of transpiration loss, but we assume this is a single source model of the Monteith (1965) type in which, in dry conditions, evaporation is given by the equation

\[
\lambda E = \frac{\Delta A + \rho c_p D/r_a}{\Delta + \gamma(1 + r_a/r_a)}
\]

where \( r_a \) is a suitably defined 'bulk stomatal resistance' and \( r_a \) is the aerodynamic resistance used by Rutter et al. (1971) *i.e.*, the resistance to momentum transfer in neutral conditions. The enhanced transpiration given by this model over that given by the MANTA model is very marked, and more than compensates for any increased interception loss. However, in this case changes in effective aerodynamic resistance generated by changes in effective source height, are very unlikely to be the origin of the difference. For pine in dry conditions, \( r_a \) is usually at least an order of magnitude greater than \( r_a \) (e.g. Gash and Stewart, 1975), and Eq. (4) is insensitive to changes in aerodynamic resistance. Clearly it is important that the cause (in SL) of this difference between a single source and a multi-layer model should be investigated, since such a difference has not previously been reported in similar model comparisons (e.g. Sinclair et al. 1976). An investigation might therefore yield new insight.
REFERENCES


Reply by P. J. SELLERS and J. G. LOCKWOOD

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Before replying to the detailed points put forward by Shuttleworth and Gash, a general point should be expanded. The MANTA pine model represented a pine canopy of known geometry and a leaf index of 4.0 as a vertical series of four plates, rather like a restaurant cake stand. This framework was then used to derive evapotranspiration rates under a variety of conditions with no thought, at the time, to the concept of 'effective' source height. At all times, the model canopy was capable of exposing a surface 8 times as large as the underlying ground surface when dry, and a wet area 3-2 times as large when saturated. (This last figure is arrived at by multiplying 4.0, the leaf area index, by 0-8, the assumed maximum proportionate wetted area). The Rutter model, on the other hand represents the evaporating surface, whether wet or dry, as being one unit area per unit ground area. (A full account of the MANTA research project may be found in Sellers (1981).)

Shuttleworth and Gash are broadly correct in attributing the greater total interception loss rate predicted by the MANTA model to the higher evaporation rates simulated for the saturated multilayer canopy. (It must be also said, however, that the very high evaporation rates while wetting up and the shorter drying out times predicted by the MANTA model have a hand in this). Shuttleworth and Gash suggest that '... it is important to establish whether the significantly enhanced evaporation rate does in fact occur as the effective source of water vapour rises in totally
wet conditions, or whether it is an artefact of the way aerodynamic resistances are treated in the MANTA model. In fact, the reason why the MANTA model usually predicts a higher rate of interception loss than an equivalent Rutter model (which incorporates the same values of p, S, Z₀ and d) has elements of both explanations. Firstly, the totally wet canopy maintains a wet surface, of 0·8 area per unit ground area, well above the height of (Z₀ + d), which is normally assumed to be the bulk source height in unilayer studies. In this position, the surface is able to make the most use of the energy available to the canopy as it is closest to the vapour sink and is exposed to a turbulent airflow. Secondly, the rest of the wet canopy and soil surface are competing for energy but as the top layer is evaporating so fast, so raising the local water vapour concentration and reducing the air temperature, a partial ‘block’ is imposed on energy fluxes to and from the lower leaf layers. This, among other factors, explains why canopies dry out from the top downwards! Whichever way one wishes to think of it, either in terms of a raised vapour source or as a lowered aerodynamic resistance, the MANTA treatment will usually predict the higher loss rate. Some physical verification for these theories is provided in the analysis of Hancock, Sellers and Crowther (in prep.). Hancock (1978) measured some canopy wetness fraction values for a stand of sitka spruce and micrometeorological variables simultaneously. It was found that the data could be used in the Rutter equation to derive the effective value of  𝑟ₐ  directly. The values so derived were found to be consistently smaller than those computed via momentum analysis for high values of C/S and correspondingly larger when C/S were small. The physical explanation for these phenomena, which entirely support the MANTA predictions, is that the effective vapour source moves from top to bottom of the canopy when drying (or as C/S diminishes), and thereby increases the apparent value of  𝑟ₐ  .

The Shuttleworth (1978) treatment of a partially wet canopy is an elegant attempt to reconcile the multilayer and unilayer approaches to the problem. However, the treatment is only partially successful as it cannot take into account the interference effects produced by the varying geometry of a vertically distributed vapour source.

Equation (3), in which the evaporation rates of the equivalent MANTA and Rutter models are compared, could be confusing. Should the ‘0·8’ on the left hand side be 0·8 or 3·2 or some intermediate number? In this context, a straight comparison of the two models’ predictions using a unilayer synopsis of the MANTA canopy is dangerous. Under certain meteorological conditions the saturated MANTA canopy can be induced to evaporate at a lower rate than the Rutter equivalent. As one might expect, an increase in the importance of the radiation term tends to reduce any differences in the two models’ predictions. Figs. (1a) and (1b) compare the interception loss rates from saturated MANTA and Rutter canopies over a range of wind and v.p.d. conditions for two levels of radiation income. For low radiation incomes (Fig. 1a), the MANTA model predicts the higher loss rates at low to medium wind speeds. At high radiation values (Fig. 1b), the Rutter model predicts slightly higher loss rates but the overall difference is reduced.

There are three principal explanations for the disparity between the Rutter and MANTA estimates of transpiration loss. Firstly, the higher interception loss rates predicted from the MANTA model effectively reduces the amount of water available for transpiration reaching the soil water store. Secondly, soil evaporation reduces the predicted canopy transpiration loss by interfering with the flux of energy reaching the lower leaf layers. (The Rutter model has no provision for soil evaporation). Thirdly, in the absence of a generally acceptable method of calculating bulk stomatal resistance the authors adapted the MANTA stomatal description for use in the Rutter equivalent model.

A single source model, like Eq. (4) was used to compute transpiration loss for the version of the Rutter model used in the MANTA project. The stomatal resistances of both surfaces of all four leaf layers were calculated using an adapted version of the model of Jarvis (1976) to compute the transpiration loss from the dry MANTA canopy. The same resistance values were summed in parallel to yield a bulk stomatal resistance value which was then used in the counterpart of Eq. (4). The ‘Rutter’ estimate of transpiration loss was higher as no account was taken of the interference effects produced by the vertically distributed canopy nor of the leaf laminar boundary layer and canopy air space resistances. For these reasons, the single source transpiration model as formulated above probably gives rise to overlarge estimates of transpiration loss. This should have been more fully explained by Sellers and Lockwood but it should be remembered that the study was primarily directed at modelling interception loss.

The critique of Shuttleworth and Gash is most useful in exploring ways in which the experience gained in operating the MANTA model might be drawn on to improve the more practical (and certainly far cheaper) unilayer models currently available. With regard to this, the following
suggestions are put forward:

(i) When it is raining, (rather than dripping), the interception loss rate from a canopy can be taken as the rate from a saturated canopy under the same conditions. The physical justification is that a continually replenished vapour source is maintained at a high level in the canopy.

(ii) The 'effective' value of aerodynamic resistance for a saturated canopy should be reduced below the level suggested by momentum studies. It should be noted that this will only be an effective course of action for 'normal British wet canopy conditions', i.e. low radiation incomes combined with low vapour pressure deficits. Quantifying the reduction in the conventionally derived value of aerodynamic resistance presents some considerable problems.

(iii) The inclusion of a minimum wetted area in the unilayer formulation such that C/S is not be allowed to drop below, say, 0.1 has two advantages. Firstly, the logarithmic drying curve of C(t) often predicted by the Rutter model (in which the canopy never dries out) would be eliminated and, secondly, the drying experiments conducted by the first author show it to be not unreasonable from a physical aspect. The experiments further showed that complete saturation of a canopy virtually never occurs, hence the maximum value of 0.8.

(iv) Transpiration loss may be calculated cheaply to an adequate accuracy by means of single layer models. The authors see no advantage in using a multilayer model for this purpose.
It is clear that the physics of interception loss from tall crops is far from being fully understood. Experimental work is being conducted by Crowther, Morgan and Sellers at Strathclyde University in order to verify or refute the MANTA predictions. Should the MANTA simulation technique be vindicated, an effective restructuring of the unlayer models may be a positive result.

REFERENCES


CORRIGENDUM


During the preparation of a sequel to our recent paper on small cumulus clouds (Kitchen and Caughey 1981, hereafter referred to as I), we discovered an error in the method of construction of the 5 second gust vectors used in I. This has a number of consequences which must be brought to the attention of readers.

(1) In section 4(a) of I, we suggest that there was inflow near the base of the stronger cloud, whereas the corrected versions of Figs. 6, 8 (see below) indicate outflow in this region.

(2) The evidence for a single 'P' shaped circulation within the clouds is not as strong as was stated in section 4(a) and the concluding remarks of I. The replacement Figs. 6, 8 show a more symmetric (i.e. double 'P' shaped) circulation for these clouds with the main up-