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CEGB RESEARCH FELLOWSHIP ON LAND SURFACE ATMOSPHERE INTERACTIONS ANNUAL REPORT 1993

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Chapter 1

Introduction and Summary

1.1 Introduction

The use of Soil Vegetation Atmosphere Transfer models (SVATs) is beginning to play an ever more important role in understanding climate change. As Global Circulation Models (GCMs) become more sophisticated and accurate in the solution of the governing circulation equations, the necessity for better boundary conditions such as land surface conditions is apparent. Hence, the work undertaken within the framework of the CEGB fellowship will continue and expand. Full use will be made of links with the Hadley Centre by supplying calibrated SVATs for different vegetation types which are then implemented into their GCM.

This report summarizes the work of Eleanor Blyth and Chris Huntingford under the CEGB Fellowship in 1993 on Land-Surface Atmospheric interactions. Chris Huntingford has been continuing the work under the supervision of A.J. Dolman who is currently working at the Winard Staring Centre, The Netherlands.

1.2 Summary

During this final year of research under the CEGB fellowship, effort has been directed towards understanding and improving each component of the Two-Layer MITRE evaporation model. Different forms of stomatal response to local climate conditions have been tested and the model has been applied to a variety of vegetation types. In particular the following have been achieved:

- Better physical representation of both the aerodynamic and stomatal resistances required by SVATs.
- Application of MITRE Model to sahelian savannah: this has highlighted areas where future improvements could be made.
- Dominant terms of SVATs are found by either direct substitution of values or through the formal technique of non-dimensionalization.
- The more complicated models can, under certain circumstances, be reduced through the use of asymptotics.
- It has been observed that model dependence on variables and parameters depends strongly on the values taken by the driving variables. This has been demonstrated in wet conditions where the models are very sensitive to the aerodynamic resistances, and in particular the roughness lengths taken. In dry conditions the stomatal resistances tend to dominate all models.
- The MITRE model can correctly model horizontal fluxes of heat from the soil to the bushes. This is important for vegetation types such as Sahelian tiger bush where the simpler Big Leaf Model fails.
- A new hypothesis is proposed where the resistance network of the MITRE Model can be extended to model aggregation effects, vastly reducing the complexity of the problem.

These ideas are discussed in the following sections.

Chapter 2

Applications and development of the MITRE model

2.1 Improvements of the MITRE model and application to fallow savannah

This section is based around the findings of Huntingford *et al.* (1994). Three models are compared, all of which describe the partitioning of net radiation into sensible and latent heat fluxes over sahelian savannah. Comparisons are made with their ability to predict the latent heat flux λE using different configurations of stomatal and aerodynamic resistances. Data from the 1990 Sahelian Energy Balance EXperiment (SEBEX) are used.

The resistance networks for all three models are given in Fig. 1. The extra resistances for the latent heat flux are due to a stomatal resistance, across which the vapour pressure decreases from saturated vapour pressure, $e_s(T)$, within the stomata, to the vapour pressure at the leaf surface. A second type of resistance at the leaf surface, a laminar boundary layer, is seen by both the sensible and latent heat fluxes. Momentum does not see this resistance: the leaves automatically set up a pressure field out into the turbulent region (Chamberlain, 1966).

The three models differ in that the vegetation can be represented as two separate components with different stomatal responses, or a single vegetation type with a simple mean stomatal response. They also differ in the complexity of the resistance network used to determine the fluxes between the surface

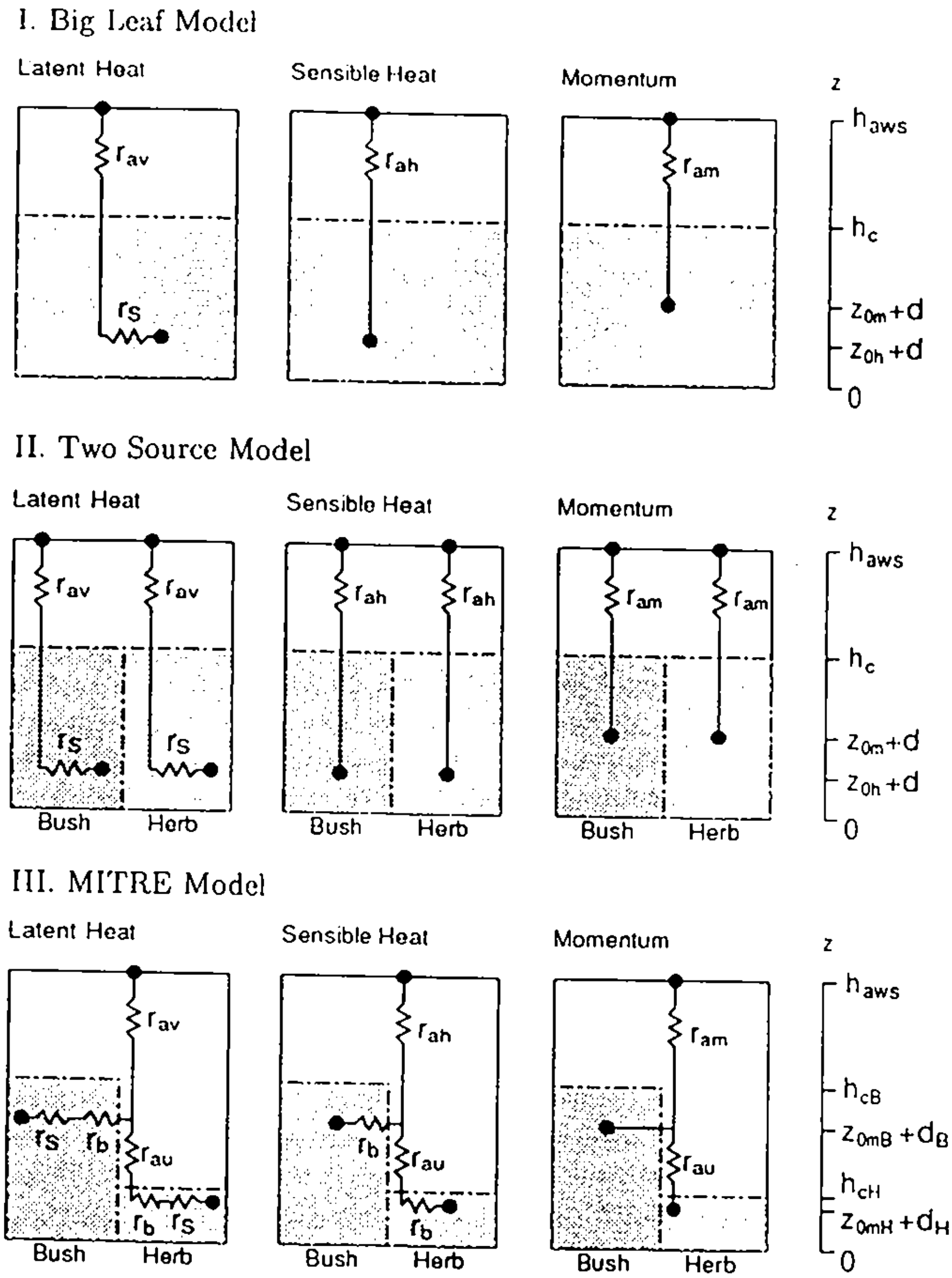

Figure 1 Resistance networks of three models to mass, heat and momentum transfer

and the lower atmosphere. In the MITRE model the resistances from both vegetation types are coupled at an internal point within the canopy where an in-canopy vapour pressure deficit is calculated. The MITRE model explicitly models the boundary layer resistances, whereas the models with the simpler aerodynamic resistance include this through a roughness length for heat z_{0_h} not equal to that for momentum, z_{0_m}.

All three models are driven with meteorological data and a value of λE calculated at each timestep. Any unknown parameters in the stomatal response were found by least squares optimization. For the Two Source and MITRE model, optimizing for both stomatal resistances simultaneously causes problems due to collinearity, that is the similar behaviour of the two functions creates large error bounds for the unknown parameters. To overcome this, the bush component is uncoupled and the bush evaporation rate compared with bush sap flow measurements. The percentage of variance explained for all three models differed by just a few percent [81.9 % - 83.6 %]. In addition systematic errors in the prediction of λE are common to all three models. For dry conditions at the fallow savannah site, if the evaporation rate is required there seems to be little to be gained using the more complex MITRE Model compared with the simple Big Leaf Model. This is almost certainly due to the stomatal resistances being significantly larger than the aerodynamic resistances and so the more complicated aerodynamic resistance network has little effect on λE. However, in models which allow different stomatal responses, there are important variations between the bush and herb stomatal responses. The herbaceous layer is less responsive to a vapour pressure deficit and solar radiation, but does have a stronger reaction to a soil moisture deficit. The parameters selected by optimizing the Big Leaf Model (which only has a single stomatal response function) lie approximately midway between those of the Two Source and MITRE models. Hence the single canopy model assumed by the Big Leaf Model does respond as an average of the two vegetation layers present.

For all models, analysis of residues between predicted and actual evaporation rate show the models to consistently overestimate in the afternoon (see Fig. 2). Future work may include a stomatal response that includes a diurnal "memory", allowing for vegetation to become water stressed in the afternoon with recharge at night. The optimization also suggests a missing aerodynamic resistance in the MITRE model between the bushes themselves and points above the herbs. This resistance would have to be put in series with the bush boundary layer resistance. Whilst over the fallow savannah, the Big Leaf Model is sufficient to predict λE, the more complicated models provide insight into the different vegetation responses to the local climate. There is evidence for certain combinations of vegetation types the Big Leaf Model *is* inadequate, for instance at tiger bush. Here only a Two Layer Model can describe the physical processes and is discussed below.

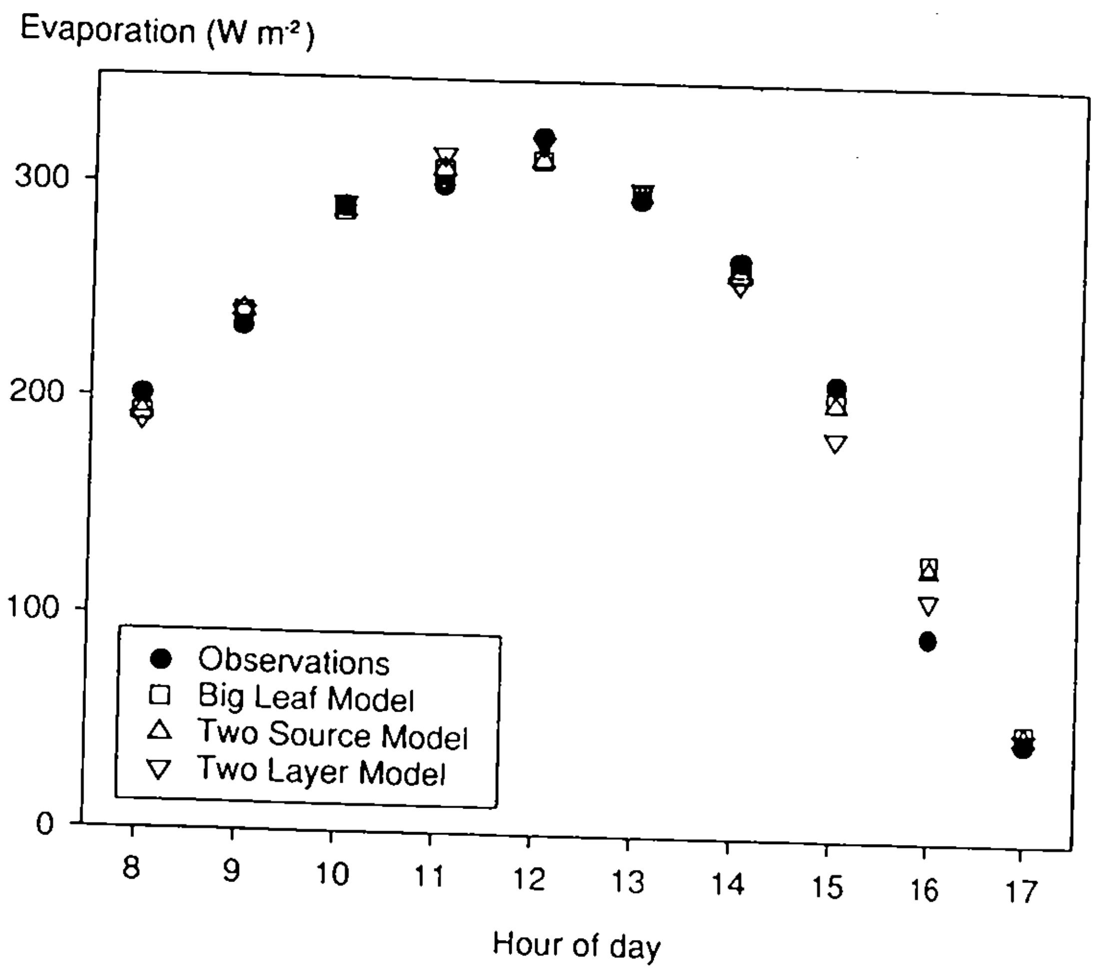

Figure 2 Modelled and measured mean evaporation rate at fallow savanna site

2.2 Modelling tiger bush with the MITRE model

The research so far has found that heterogeneous surfaces can be treated as a patchwork terrain, solving the energy balance equations over each patch separately (Blyth *et al.*, 1993). However, after studying aggregation of heterogeneous surfaces with a flat numerical model (in which the vegetation has no height) there is some concern that at small scales this modelling approach might not work. The height difference of surfaces can affect the thermodynamic balance of small scale heterogeneity by increasing the edge effects (Klaassen, 1991).

At very small scales of heterogeneity, the edge effects dominate over the vertical energy balance and the surface can be modelled as a sparse canopy, (Dolman, 1993; Shuttleworth and Wallace, 1985). Modelling strategies are therefore available for two extreme length scales, sparse canopies for the very small and patchwork terrains for the very large. To identify the length scale of the transition between these two modelling approaches, a study is made of a surface whose length scale is larger than that usually treated as a sparse canopy and smaller than that usually treated as a patchwork terrain (Blyth and Harding, 1994). The tiger bush in the Sahel has patches of 4 m high vegetation and bare soil with a horizontal length scale of about 50 m. Measurements of heat flux and surface temperature were made over the tiger bush during the HAPEX-Sahel programme which took place during August to October of 1992 (Goutorbe et al., 1993).

Two dual source models were applied to the data (models II and III in Fig. 1). The ability of the models to fit the data indicated the aggregation processes which are unresolved by the measurements. The first assumes that all the fluxes act vertically and that there is a complete energy balance between the atmosphere and each surface. This can be modelled by calculating the heat fluxes from each surface with the Penman- Monteith equation using the same humidity deficit above both surfaces. This is the Two Source Model. The second assumes that there are horizontal fluxes of heat between the two surfaces so that there is not a vertical energy balance for each surface. This can be modelled by calculating the heat fluxes from each surface with the Penman-Monteith equation using a humidity deficit within the canopy. This is the "sparse canopy" model proposed by Shuttleworth and Wallace (1985), which was adapted by Dolman (1993) for widely spaced vegetation and described more fully in Huntingford *et al.*, (1994). It will be referred to here as the MITRE Model. Both the MITRE and Two Source Models have identical arrangements of resistances as those used for fallow savannah. Fig 1 shows the layout of the resistances of the two models.

The results of the Two Source Model are the worst. The r.m.s. error of predicted heat flux and surface temperature is 34 W m^{-2} and 1.6 °C respectively. The parameters of the minimum stomatal resistance $r_{s_{min}}$ (bush) which gives the best fit is 4 s m^{-1}. This value for $r_{s_{min}}$ (bush) is unrealistically small and, along with the high errors, indicates the failure of this model. The errors of the coupled model are similar to the big leaf model; 26 W m^{-2} and 1.6 °C for the heat and surface temperature respectively. The value of $r_{s_{min}}$ (bush) which gives these results is 24 s m^{-1}.

The failure of the patch model and success of the coupled model imply that there is a significant horizontal flux of heat below the tops of the canopy of the tiger bush. The MITRE Model was originally designed to deal with crops where the spacing between the vegetation is less than that of the crop height. It is therefore of great interest that the sparse canopy principle applies to the tiger bush where the space to height ratio is 10:1; it appears that the MITRE Model can be used where there is significant horizontal flow of heat between the surface types. There must be some vertical heat transfer between the atmosphere and the bush and soil separately, but at this length scale, this vertical transfer is of equal significance as the horizontal transfer. At greater length scales of variation the Two Source Model is shown to be an appropriate description of the aggregation process. The question of the length scale at which horizontal heat transfer domination changes to vertical heat transfer domination remains to be answered. However, this study of the tiger bush gives a useful reference point on this question.

2.3 Modelling effective z_{0_h} for a sparse canopy with the MITRE model

Using the parameters of the MITRE Model optimised on the tiger bush, it is possible to demonstrate how the effective value of z_{0_h} for such a sparse canopy depends on the environmental conditions (Blyth and Dolman, 1994).

Fig. 3 shows how z_{0_h} varies with two environmental properties; available energy and humidity deficit. At low values of available energy and at high values of humidity deficit, the sensible heat flux of the bushes can become negative. The high evaporative rates of the canopy are sustained by heat drawn from the air above the soil. Therefore, average sensible heat fluxes can be low, while the average surface temperature remains high; this results in low values of z_{0_h}.

Fig. 4 shows how z_{0_h} varies with the percentage cover of vegetation. When the vegetative cover is zero, the value of z_{0_h} is that of the soil, and when the coverage is 100 %, the value for z_{0_h} is that of the vegetation. With partial vegetative cover the value of z_{0_h} is biased towards the value for the soil and the lower the surface resistance of the vegetation, the lower the value of z_{0_h}.

Fig. 5 shows how the ratio $z_{0_h}/z_{0_{h'}}$ varies between 20 and 30 with percentage cover of vegetation of a sparse canopy. The value $z_{0_{h'}}$ is the value of the roughness length for heat and vapour that would be calculated from the traditional equation of a tenth of the vegetation height.

The lower curve in Fig. 5 is the result of assuming a vegetation substrate instead of soil: the roughness length is not changed but the surface resistance of the substrate is set at 100 s m^{-1}. In this case the ratio $z_{0_h}/z_{0_{h'}}$ is about 5.

The thermodynamic relationship between vegetation and soil in a sparse canopy can thus account for at least one order of magnitude difference between the roughness length for heat of a homogeneous surface and a sparse canopy.

2.4 Using the MITRE model to predict forest rainfall interception loss

A complete model to describe forest rainfall interception losses from a storm includes a period of wetting up, saturation and drying out (Gash, 1979). Implicit in these models is a calculation of $\overline{\lambda E}$, the mean evaporation rate from the vegetation when fully saturated. An estimate of this can be made by running evaporation models with zero stomatal resistance, that is the water is freely evaporating off the surface of the leaves.

Two models, the Big Leaf Model and the MITRE model are used to calculate $\overline{\lambda E}$. The driving data are meteorological data collected from Les Landes Forest during the HAPEX-MOBILHY experiment, fully described in

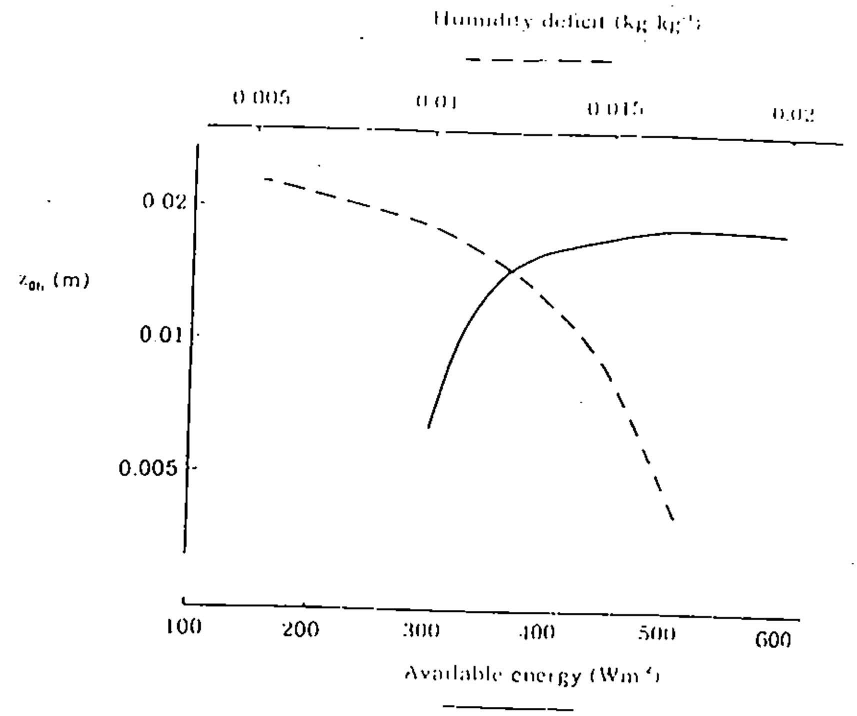

Figure 3 Dependance of tiger bush roughness length for heat on available energy and humidity deficit

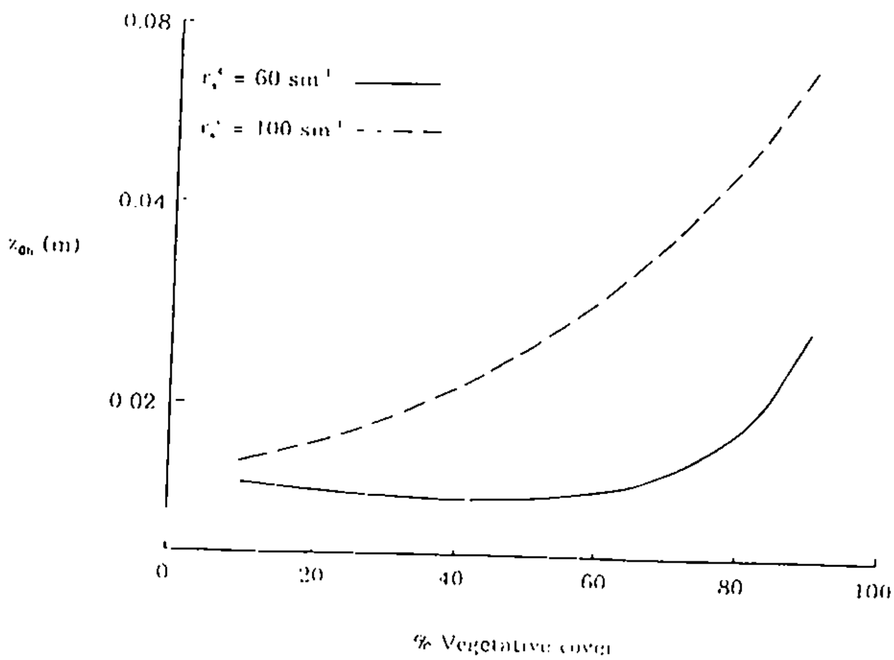

Figure 4 Dependance of tiger bush roughness length for heat on percentage cover of vegetation

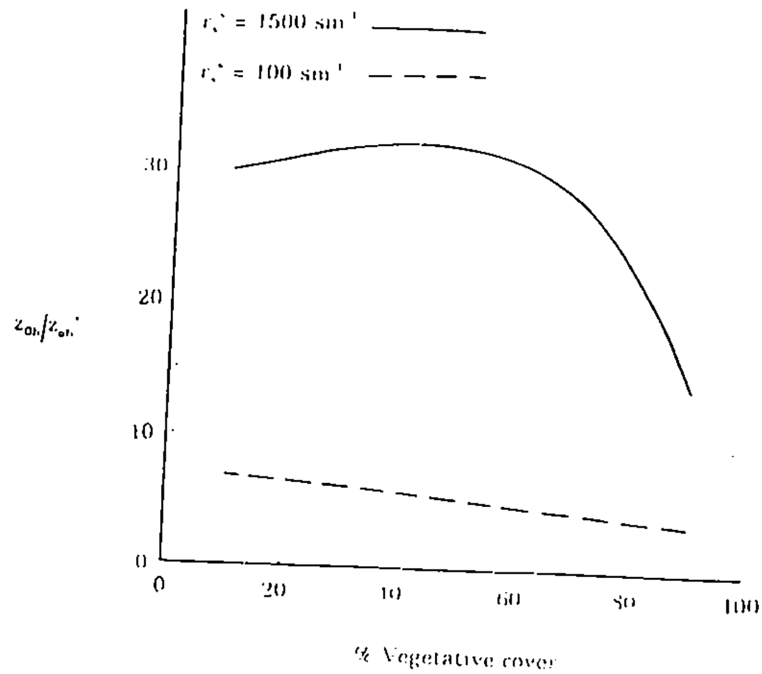

Figure 5 Ratio of modelled and measured roughness length against percentage cover of vegetation

Gash *et al*, 1994. The key result is that the models' prediction of $\overline{\lambda E}$ differs by a factor of nearly four (whereas the previous section implies that with the stomatal resistances included, the predictions of different models are likely to be similar in dry conditions). The Big Leaf Model predicts an evaporation rate from the canopy (ignoring an understorey contribution from the bracken) of $\overline{\lambda E}$ = 23 W m^{-2}, whilst the MITRE model (which explicitly models the bracken contribution) gives $\overline{\lambda E}$ = 82 W m^{-2}. The trees cover 45 % of ground cover although the MITRE model predicts the bracken contribution as only 21 % of the total evaporation rate.

The value calculated from measurements gives 58 W m^{-2} and so both models still need improvement. A suggestion is made below as to how the MITRE model may be improved, but in the meantime the model differences must be understood. With zero stomatal response, both models become highly sensitive to the aerodynamic resistances. With a different aerodynamic resistance configuration, the MITRE model cannot reduce to the Big Leaf Model. However, a good approximation by the Big Leaf Model should be possible, suggesting the roughness length for sensible heat z_{0_h} used in the Big Leaf Model aerodynamic resistance during dry conditions does not carry over to a saturated canopy.

During dry conditions, the transfer of water vapour is dominated by the stomatal resistances at both the understorey and canopy level. With both stomatal resistances being of comparable size, the overall resistance presented to evaporation from both levels is only slightly different. However, in wet conditions when only the aerodynamic resistances are encountered, then the resistance from the understorey and up out of the canopy is relatively far larger than that from the canopy. Hence the overall evaporation rate has a different division between mass flux from the canopy and that from the understorey. However, the profile of momentum absorption is unchanged and so a different value of z_{0_h} is required in wet conditions.

Analysis of the MITRE Model over fallow savannah suggests an additional resistance may be required linking the upper canopy with the resistance network from the understorey. It will be especially important in modelling interception losses to get this correct and will probably produce a value of $\overline{\lambda E}$ nearer the measured value of 58 W m^{-2}.

2.5 Modelling scale effects with the MITRE model

Using a numerical model, the average evaporation from a heterogeneous surface is shown to be a function of the length scale of heterogeneity. The evaporation of a surface is enhanced when the wind blows from a dry to a wet surface and so the more dry-wet edges there are per unit area, the more evaporation there will be. This feature can be represented for a mixture of two surfaces using the three resistance model given in Fig. 6. Both surfaces have a surface and aerodynamic resistance. A third aerodynamic resistance is used to quantify the height h_{ref}, which the two surfaces use as a reference height for the calculation of evaporation and sensible heat. The lower the apparent reference height, the greater the evaporation flux. Using results from the numerical model and data collected from tiger bush in the Sahel, an empirical formula is developed that specifies the correct value for the third resistance (and implicitly h_{ref}). This is described more fully in Blyth, (1994).

Many of the issues of aggregation can be absorbed into the model. The nonlinearity of the relationship between evaporation and the surface parameters is accommodated by calculating the evaporation from the two surfaces separately. The advection effects are modelled by increasing the interaction between the two surfaces whilst any extra advection that takes place as a result of the different heights of the surfaces can be explicitly described by setting $r_1 \neq r_2$.

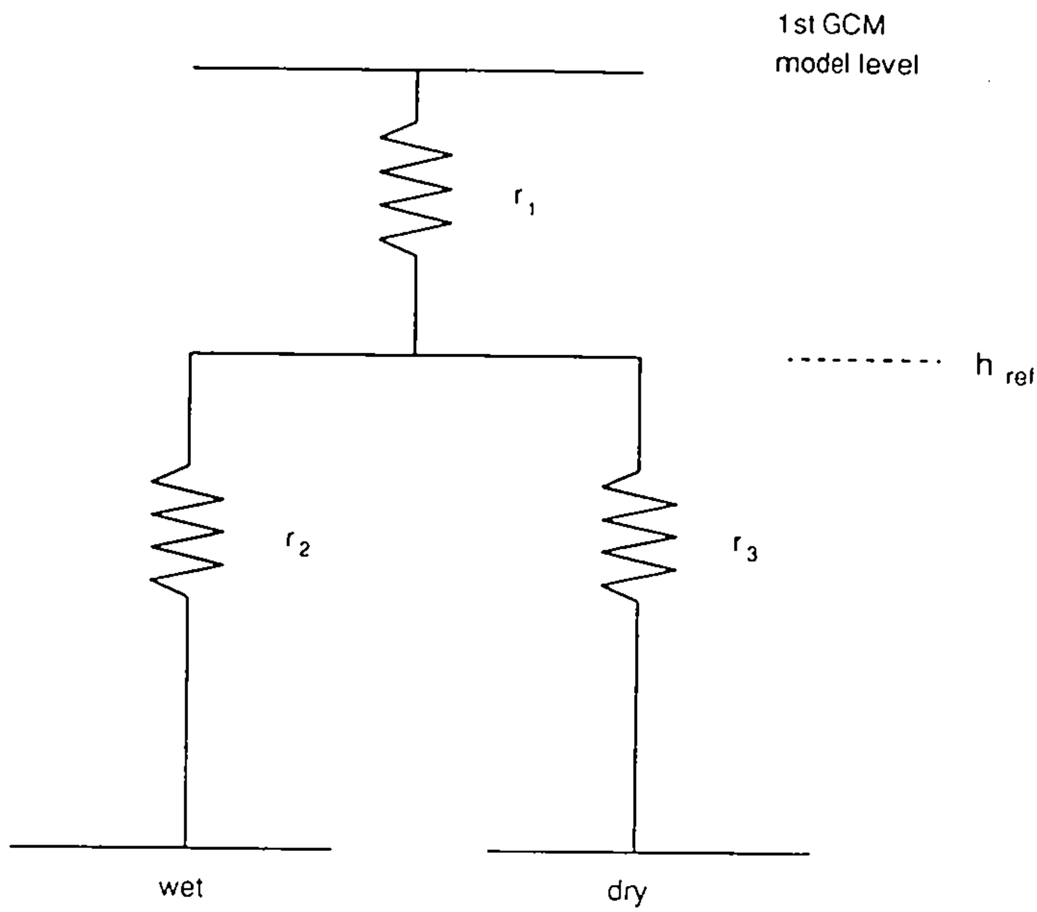

Figure 6 Resistance network used to model aggregation effects on a larger scale than the MITRE model

Chapter 3

Non-MITRE work

3.1 Non-dimensionalization of SVATs

Tools frequently used in applied mathematics are non-dimensionalization of equations and asymptotics. Non-dimensional variables are scaled such that their absolute value lies between zero and one. The scalings are then grouped with the physical variables into non-dimensional parameters which are given a numerical value. Non-dimensional parameters within equations that are either very large or very small can be used to eliminate or simplify terms. This may often be achieved through simple expansions (such as the binomial). By showing the dominant terms in equations, it is easy to understand the interplay between different models, and when a more complicated model is appropriate. For vegetation modelling, further questions may be quickly answered. By normalising with the same scalings, direct comparisons may be made between vegetation types whilst for one particular form of land cover, it can be seen how different terms dominate according to the varying driving climatological variables.

The scaling approach to SVATs appears to be in its infancy. Huntingford, (1994) sets out the notation and the technique applied to the simple Penman-Monteith Big Leaf Model. Driven by data from dry daylight hours at both Thetford Forest and the fallow savannah site in the Sahelian Energy Balance EXperiment (SEBEX), differences in the vegetation responses are seen. As a generalisation, the prediction of evaporation rate from the Penman Monteith equation for the fallow savannah requires all terms in the equation. However, for Thetford forest, the large values of bulk stomatal resistance r_S, vapour pressure deficit D and small values of aerodynamic resistance allow a good approximation the Penman Monteith equation $\lambda E \approx \rho c_p D / r_S$ where ρ is the air density and c_p the specific heat of air. This equation is dimensional: having finished working in the non-dimensional framework, it is necessary to return to dimensional quantities to answer the original modelling problem. The extent to which simplification of small terms by elimination is allowable is usually dictated by the accuracy required and the accuracy of measurements.

This is an area with scope for future work. It will be possible to formalise when the Big Leaf Model is adequate to predict λE, and when a multi-layer model is required. Intercomparison of vegetation types will be easier and as a further benefit, normalised sensitivity analyses can be readily calculated.

3.2 Collaborative work regarding stomatal resistance

The bulk stomatal conductance g_S (inverse of the bulk stomatal resistance) used in SVATs is often represented:

$$g_S = LAI . g_{ST_{max}} \prod_i f_i(X_i, a_{i,j})$$

where $0 \leq f_i \leq 1$, X_i are local environmental variables and $a_{i,j}$ are unknown parameters, found by optimization of evaporation models against measured values of λE. The functions f_i account for how far the local conditions are from the ideal when the stomata are completely open and hence at maximum conductance. Current variables X_i include the temperature T, humidity deficit D, soil moisture content Θ and incoming solar radiation R_{solar}. The functions $f_i(X_i, a_{i,j})$ have been derived from controlled laboratory experiments where each individual X_i has been varied. However, there are reasons to believe these results will not carry over directly into the field. Mentioned above is the lack of a diurnal water stress function, restricting the late afternoon evaporation rate. Future work will model this at each hour as a function of earlier evaporation during that day, and so an integration is required. However, this will complicate the models for the evaporation rate can no longer be calculated from instantaneous meteorological measurements.

Professor J.L. Monteith (Institute of Terrestrial Ecology) has discussed the interesting point that a "vapour pressure deficit" sensor has never been found in the stomatal control of a plant. He has suggested the response observed during both laboratory and field experiments is actually caused by a different mechanism, which may be interpreted as being a vapour pressure dependence. Instead it is proposed that a stomatal control exists whereby the plant recognises a high evaporation rate and closes its stomata. The new proposed function is given by $f_i(\lambda E; a_i) = 1 - \lambda E/a_i$ and this makes an evaporation equation implicit in λE. The value of a_i is allowed to depend on the soil moisture content. Optimization runs to determine unknown parameters $a_{i,j}$ using data collected from Thetford Forest (Stewart, 1988) demonstrate a comparable overall degree of accuracy replacing $f_i(D)$ with the new function above. However, the two models do give different predictions for various parts of data space suggesting both models to be more accurate in certain circumstances, but neither performing very well overall. This leaves scope for some accurate statistical tests to determine a response function that may be a combination of these two stomatal representations.

Chapter 4

Future work

4.1 Future work

Four key new areas will be studied. Firstly the SVAT models will be extended to include CO_2 fluxes. Work is already under way to collaborate with the Hadley Centre and the Institute of Terrestrial Ecology to implement the PGEN model which is an integrated model of leaf photosynthesis, transpiration and conductance (Friend, 1993). The model is based on the premise that stomatal response to the environment is such as to maximise the instantaneous carbon flux. The photosynthetic rate is assumed to be an increasing function of leaf water potential. Hence an increase in stomatal conductance will lead to an increase in the internal CO_2 concentration which is favourable for photosynthesis, but a decrease in leaf water potential which is not. Hence there always exists an optimum stomatal conductance. This model provides a completely different way of calculating the stomatal conductance and hence λE. The model can be compared with data along with existing models - indeed new insight into the existing empirical description of g_S may be obtainable.

Secondly model development should include better representation of soil processes. These must take account of the variations in hydraulic conductivity between relatively near sites, thereby providing an interesting problem in spatial averaging. These models will be calibrated against data with the eventual aim of inclusion in multi-layer models (e.g. MITRE model). The problem of spatial averaging is also of interest when describing fluxes for

GCM squares, and this challenging third problem will be studied using both analytical and numerical tools. The range of scales in decreasing order can be see as GCM - Mesoscale - Local 2-D Boundary Layer - SVATs. Not only must each scale be understood, but also the way it feeds into the next larger scale as a subgrid process. This opens the exciting opportunity of SVATs allowing the data to provide more than an understanding of vegetation at just one point.

Fourthly, we return to GCMs where our vegetation parameterisations provided as boundary conditions will provide insight into the effects of climate change.

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