A Description of Rainfall Interception over Large Areas

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ABSTRACT

A new scheme is developed for describing interception at spatial scales comparable to the typical resolution of climate models. The scheme is based on the Rutter model of interception and statistical description of the subgrid-scale spatial variability of canopy storage and rainfall. The interception loss simulated by the new scheme is significantly smaller than those simulated by other schemes that do not include considerations for spatial variability. The explanation of this result is partly in the enhancement of spatially averaged canopy drainage due to the large local drainage from the few buckets of large canopy storage.

The relative reduction in interception loss simulated by the new scheme may explain the overestimation of interception loss by climate models that do not include the effects of spatial variability on interception processes.

1. Introduction

Vegetation affects land-surface hydrology in many different ways. It intercepts rainfall before reaching the ground surface and controls the subsequent rates of canopy evaporation and canopy drainage. The significance of these interception processes increases with the density of the vegetation layer. In forest environments, interception plays a significant role in the partition of rainfall into evaporation and runoff. The coverage of the land surface by a vegetation layer increases surface roughness and enhances eddy transport of heat and water vapor near the surface. Because of this physical effect, evaporation of intercepted rain occurs at rates that are higher than potential evaporation. Evaporation of intercepted rain, which is usually referred to as interception loss, accounts for a significant part of total rainfall. It ranges from a few percent to about 25% depending on the nature of rainfall and the size of canopy storage capacity. The main objective of interception modeling is to describe accurately the partition of total rainfall into canopy drainage and interception loss.

The recent interest in describing surface hydrologic processes at large spatial scales is motivated by the need for including land-surface hydrology in climate models. The typical spatial resolution of a climate model is in the order of hundreds of kilometers. Hence, it is necessary to develop descriptions of surface hydrologic processes over such large areas. The early versions of land-surface hydrology parameterizations did not include representation of interception processes. But more recent schemes such as the Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson et al. 1986) do include descriptions of interception. The BATS treatment of interception is described in appendix A.

Dickinson and Henderson-Sellers (1988) used BATS as part of a climate model in studying the possible impacts on global climate due to deforestation of the Amazon Basin. Figure 1 shows the simulated interception loss over the whole Amazon Basin compared to interception loss measured at a single site in the basin. Although the two quantities are not perfectly comparable, it seems that the simulations overestimated interception loss by about 150%. Total evaporation was also overestimated in these simulations. A partial explanation for those results is given by Dickinson (1989), overestimation of interception loss is partly due to overestimation of surface net radiation. Another possible explanation is the use of large canopy storage capacity. But Shuttleworth and Dickinson (1989) argue that overestimation of net radiation by about 70% or the use of large canopy storage capacity cannot wholly explain the large overestimation of interception loss. They suggest that a much more serious source of error is the neglect of spatial variability in rainfall. Shuttleworth (1988b) developed a scheme for parameterizing interception that treats rainfall as a spatially variable process but assumes that canopy storage is constant in space. The scheme is described in appendix B.

In a recent paper, Dolman and Gregory (1992) addressed the problem of parameterization of rainfall interception in climate models. They studied two interception schemes, which include some of the effects of spatial variability in rainfall. Although these schemes

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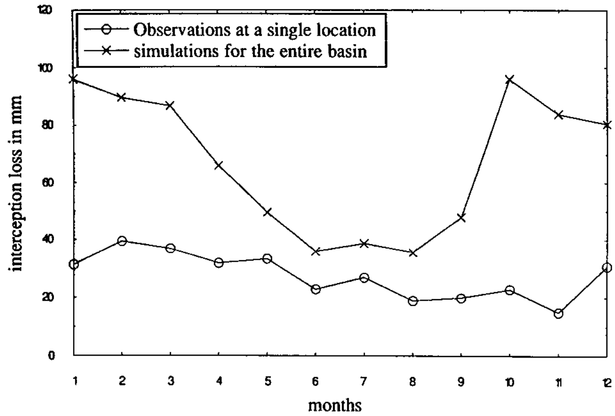

FIG. 1. Comparison of interception loss from the simulations of Dickinson and Henderson-Sellers (1988) with the observations of Shuttleworth (1988a).

assume that rainfall is distributed over a small fraction of the grid-cell area, the depth of water on the canopy is assumed constant over the entire area of the grid cell. The two interception schemes are similar to the scheme of Shuttleworth (1988b).

Lean and Warrilow (1989) used the United Kingdom Meteorological Office model in their simulations of the Amazon climate. The simulated interception loss at the model grid point that corresponds to the site of the data in Fig. 1 is larger than the observed interception loss by 184%. Total evaporation is overestimated by 15%. Lean and Warrilow (1989) argue that "overestimation of canopy evaporation is probably present in other land surface schemes and this may be due to the extension of single point description of the rainfall interception process to the grid-scale area in a region where convective rainfall events dominate." We totally agree with these conclusions.

Overestimation of interception loss in climate models is a serious problem. Shuttleworth (1988a) estimated that interception loss at a single site in the Amazon basin is 25% of the total evaporation and that evaporation accounts for about 90% of the net radiation at the surface. Under these conditions, overestimation of interception loss may result in a significant error in the partition of net radiation into latent and sensible heat fluxes.

Although interception models may provide accurate description of the process at a point, as demonstrated by Rutter et al. (1975), using these descriptions in climate models results in large errors. It seems that subgrid-scale spatial variability in rainfall and canopy storage play a significant role that tends to reduce the spatially averaged interception loss. It is evident that the basic question in representation of interception processes in climate models is how to describe interception over large areas considering both the basic physics of the process at a single location and the spatial variability within the large area. This paper will try to answer that question.

Our approach is a combination of the physical description of interception at a point and statistical treatment of the subgrid-scale spatial variability of rainfall and canopy storage. The Rutter model is used in describing interception at a point. The physical parameters that control interception at a single location are assumed constant in space. Analytical expressions are derived to relate the spatial average of canopy drainage and interception loss to the spatial average of canopy storage. These expressions are based on reasonable assumptions about the spatial distributions of rainfall and canopy storage. This set of relations are proposed as a new interception scheme designed to describe the process over large areas and hence provide the suitable parameterizations of interception processes in climate models.

In the following, the Rutter model of interception is described in some detail. The derivation of the new interception scheme is then presented. An off-line version of BATS is used in comparing the new scheme with previous schemes. The paper concludes by discussing the results of these comparisons and the limitations of the new interception scheme.

2. Rutter model of interception

This model was introduced by Rutter et al. (1971) to provide a predictive tool of rainfall interception. Canopy storage is created by rainfall and depleted by canopy drainage and evaporation. (Canopy storage is a variable of the interception processes; it is different from canopy storage capacity, which is a parameter of the canopy.) The Rutter model specifies the functional dependence of canopy drainage and canopy evaporation on canopy storage. Canopy drainage is described by

$$D_r = Ke^{(C/b)}, \qquad (1)$$

where D_r is canopy drainage, C is canopy storage, and K and b are constants characteristic of the canopy. It is important to note the exponential dependence of canopy drainage on canopy storage. This strong dependence results in rapid depletion of excessive local storage.

Evaporation from the canopy has two components: interception loss and transpiration. It is described by

$$e = \frac{C}{S} e_c + \left(1 - \frac{C}{S}\right) e_t, \quad 0 \leq C \leq S,$$
$$e = e_c, \quad C \geq S, \qquad (2)$$

where e_t is transpiration by the plant, e_c is evaporation from wet canopy, and S is a constant characteristic of the canopy. Here S is the amount of water retained by the canopy after being completely wet and then drained for a "sufficiently" long period.

Canopy storage is added by rainfall and depleted by drainage and evaporation. The rate of change of canopy storage is given by

$$\frac{\partial C}{\partial t} = (1 - p)P - \frac{C}{S} e_c - D_r, \quad (3)$$

where p is a fraction of rain falling directly to the ground and P is rainfall.

The parameters of the model are S, p, K, and b. Calibration of the model requires estimation of these four parameters. Terms S and p are estimated from data of throughfall and total rainfall; S is the intercept of the rainfall-throughfall curve corresponding to storms with negligible interception loss, and p is the slope of rainfall–throughfall curve corresponding to storms with total depth smaller than S. The estimate of p is used in computing canopy drainage from data on rainfall and throughfall. The estimates of p and S can then be substituted in (3) to compute canopy storage from rainfall data. Terms K and b are estimated from a regression between the canopy drainage and canopy storage.

Rutter et al. (1975) extended the model to account for stemflow and used the model in describing interception in several catchments in England. The model was successful in predicting observed interception loss with reasonable accuracy. In a recent study by Shuttleworth (1988a), the Rutter model was successfully used in describing interception in the Amazon basin, which indicates that the model is robust and capable of describing interception in the rainforest environment. The results of these two studies suggest that the Rutter model provide an adequate tool for describing interception processes at a point.

The exponential dependence of canopy drainage on canopy storage results in large drainage for large canopy storage. Hence, when applying the model in describing interception processes using real data (e.g., Rutter et al. 1975), it is observed that canopy storage does not exceed a maximum of about 2 or 3 mm. The Rutter model is modified here to include a maximum limit for canopy storage, C_m, the maximum storage that the canopy can hold at any instant of time. This limit constrains primarily (3) such that C does not exceed C_m. Equation (1) is also modified to

$$D_r = Ke^{(C/b)}, \quad C < C_m,$$
$$D_r = Ke^{(C_m/b)}, \quad C \geqslant C_m. \quad (4)$$

The integrations that will be carried in the next section require that the mathematical form of the drainage function converges for all possible values of canopy storage. This is the reason for making this modification. To explain the physical meaning of C_m, one can resort to the analogy between the canopy layer and the soil layer. If S is the parameter of the canopy that corresponds to the field capacity of the soil layer, then C_m is the equivalent to the product of soil porosity and the total soil depth. In the next section, the Rutter model is used in describing interception at every point within the large area.

3. A description of interception over large areas

A new interception scheme is developed in this section. It combines the Rutter model and statistical description of the spatial variability in rainfall and canopy storage. It is assumed that rainfall is distributed in space according to

$$fp = (1 - q_P)\delta(P - 0) + \frac{q_P^2}{E(P)} e^{-[q_P P/E(P)]}, \quad (5)$$

where P is rainfall at any point in space, q_p is the fraction of the area with $P > 0$, $E(\ )$ denotes the expected value, and δ denotes the Dirac delta function. The observations of Eagleson et al. (1987) support the assumption of exponential distribution for rainfall.

Canopy storage controls the local amounts of canopy drainage and evaporation. It is assumed that canopy storage is distributed in space according to an exponential distribution. In absence of any observations of the spatial distribution of canopy storage, the choice of the exponential is a matter of convenience. The assumption is justifiable when rainfall variability is a major causal factor for variability in canopy storage. It is assumed that canopy storage is distributed in space according to

$$f_C = (1 - q_C)\delta(C - 0) + \frac{q_C^2}{E(C)} e^{-[q_C C/E(C)]}, \quad (6)$$

where C is canopy storage at any point in space, $E(C)$ is the spatially averaged canopy storage, and q_c is the fraction of the area with $C > 0$.

The spatially averaged canopy drainage is obtained by taking the expected value of both sides in (3). Here $E(D_r)$ is given by

$$E(D_r) = \int_{C=0}^{\infty} D_r(C) f_C dC$$
$$= \left\{1 - q_c + \frac{q_c^2 b}{[bq_c - E(C)]}\right\} K$$
$$+ \left\{q_c + \frac{q_c^2 b}{[bq_c - E(C)]}\right\}$$
$$\times Ke^{-\{[bq_c - E(C)]C_m/bE(C)\}}. \quad (7)$$

The above expression relates the spatial average of canopy drainage to the parameters of the Rutter model (K, b, and C_m) and the parameters of the distribution of C [$E(C)$ and q_c]. Figure 2 shows $E(D_r)$ as function of $E(C)$ for different values of q_c. Here $E(D_r)$ decreases with q_c for small values of $E(C)$ and increases with q_c for large values of $E(C)$. Figure 3 compares the drainage function of the Rutter model and that of the scheme

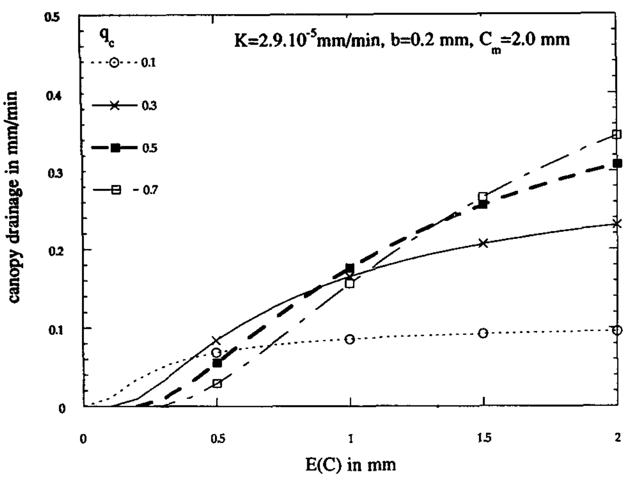

FIG. 2. Drainage function of the new interception scheme.

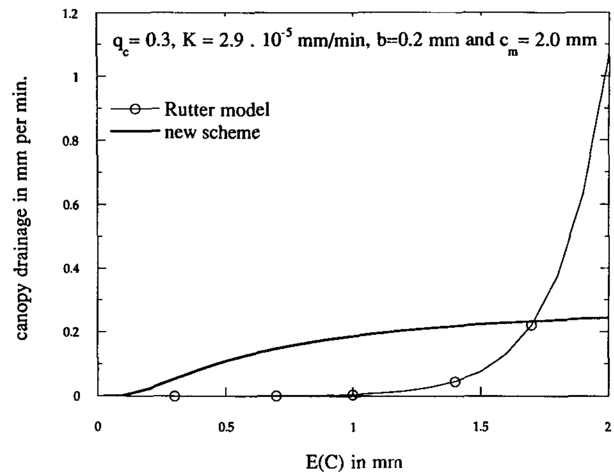

FIG. 3. Comparison of the drainage function of the Rutter model and the drainage function of the new interception scheme.

developed in this section, it compares (1) and (7). The new scheme shows enhanced canopy drainage for small values of $E(C)$ and reduced drainage for large values of $E(C)$. Average canopy storage amounts are usually in the order of 1 mm or less, which falls in the enhancement range for typical values of the Rutter model parameters.

The spatially averaged evaporation is obtained by taking the expected value of both sides in (2). Term $E(e)$ is given by

$$E(e) = \int_{C=0}^{\infty} e(C) f_C dC$$

$$= e_t + (e_c - e_t)\frac{E(C)}{S}(1 - e^{-[Sq_c/E(C)]})$$

and

$$E(e') = e_c \frac{E(C)}{S}\{1 - e^{-[Sq_c/E(C)]}\}, \quad (8)$$

where e' is interception loss. Figure 4 shows $E(e')$ normalized by e_c as function of $E(C)$ for different values of q_c. Normalized interception loss increases with $E(C)$ and approaches an asymptotic limit equivalent to q_c consistent with the mathematical form of (8). Physically, as the average canopy storage increases, a fraction of the total area, q_c, will have water available for evaporation.

Throughfall has three components: the fraction of rain falling directly to the ground through gaps in the canopy, drainage from the canopy, and rainfall in excess of drainage at locations with maximum canopy storage. The spatial average throughfall is given by

$$E(T) = pE(P) + E(D_r)$$

$$+ \int_{C=C_m}^{\infty}\int_{P=D_m/(1-p)}^{\infty} [(1-p)P - D_m - e'(C)]$$

$$\times f_C f_P dP dC = pE(P) + E(D_r)$$

$$+ [q_C(1-p)E(P) - q_C q_P e_C]$$

$$\times e^{-\langle[(q_C \cdot C_m)/E(C)] + \{(q_P \cdot D_m)/[(1-p)\cdot E(P)]\}\rangle}, \quad (9)$$

where D_m is $D_r(C_m)$.

The rate of change of the spatially averaged canopy storage is obtained by taking the expected value of both sides in (3). The derivation of the continuity equation for the new scheme is described in appendix C.

The above equations are the mathematical expression of the new interception scheme. In the next section, this scheme will be tested and compared to other descriptions of interception.

4. Simulations

An off-line version of the BATS is used in testing the new interception scheme. It is driven by the following forcings: solar radiation, above canopy temperature, above canopy humidity, and a time series of surface rainfall. The forcings are designed to simulate

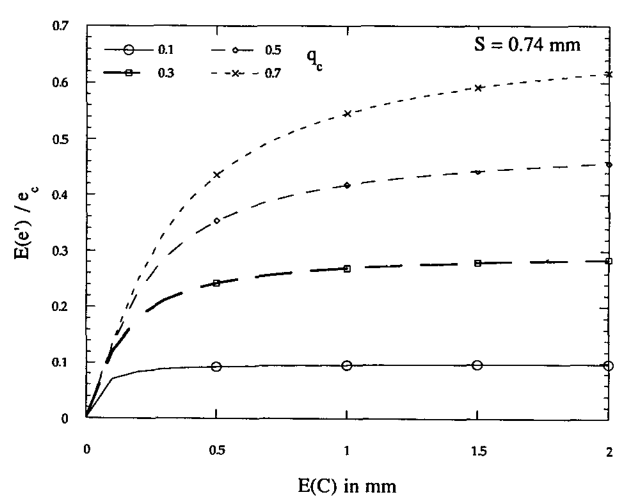

FIG. 4. Interception loss function of the new interception scheme.

a typical rainforest environment. The forcings are described in Table 1.

The rainfall series is generated using the stochastic model of Rodriguez-Iturbe and Eagleson (1987). The model simulates the rainfall rate process in space and time for each storm. The storm-arrival process is described by a nonhomogeneous Poisson process that favors occurrence of storms in the afternoons. This is consistent with the recent observations of Lloyd (1990) in the Amazon Basin. The parameters of the model are selected to simulate convective storms that are characteristic of the rainforest environment. The rainfall simulated by the model is averaged in space over an area of 10 000 km^2. The total duration of the simulation is 2 months. The parameters of vegetation and soil are specified according to those of rainforest conditions from Tables 2 and 3 of Dickinson et al. (1986). The Rutter model parameters are specified according to those calibrated for an Amazonian rainforest and described in Shuttleworth (1988a).

The scheme is compared to the following alternative descriptions: the Rutter model, the BATS treatment of interception that is described in appendix A, and the Shuttleworth scheme that is described in appendix B. Figure 5 shows normalized interception loss, which is interception loss divided by the total rain, as function of the wind speed over the canopy. Wind speed is a surrogate for potential evaporation since the two quantities are linearly related. Each point in Fig. 5 represents a 2-month simulation. The results of the Rutter model, the Shuttleworth scheme, or the BATS interception are marginally different from each other, but the new interception scheme produces significantly less interception loss. For conditions similar to those in the tropics, that is, wind speeds in the order of 1 m s^{-1}, the new interception scheme results in interception loss that differs by a factor of 2 from that of the BATS interception.

The significant reduction in interception loss is explained by Fig. 3. It compares the drainage functions of the Rutter model and the new interception scheme, (1) and (7), respectively. Including the spatial variability in canopy storage results in enhanced drainage for small average canopy storage. Enhancement of canopy drainage comes from the buckets of large canopy storage that result from randomly distributing the canopy storage within the subgrid box and recalling the exponential dependence between local drainage and local canopy storage. The enhancement of average canopy drainage reduces the amount of intercepted water available for evaporation and that significantly

TABLE 1. Description of the model forcings.

Maximum solar radiation at the surface	890 W m^{-2}
Average above canopy temperature	300 K
Daily range of above canopy temperature	6 K
Relative humidity above the canopy	80%
Mean of the rainfall series	220 mm $month^{-1}$

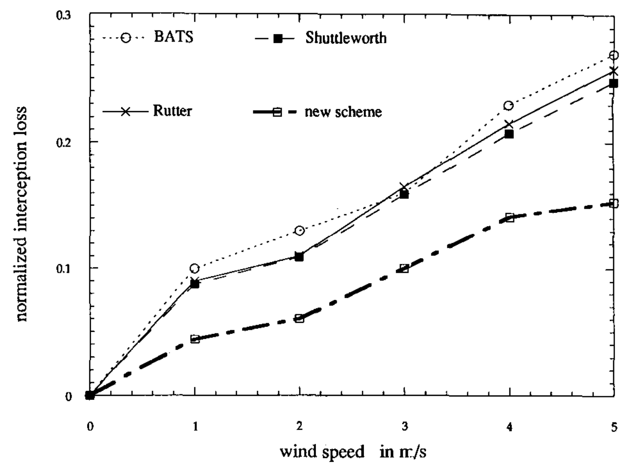

FIG. 5. Comparison of interception loss simulated by the Rutter model, the BATS interception, the Shuttleworth interception scheme, and the new interception scheme ($q_C = q_P = 0.3$).

reduces interception loss. Another reason for the reduction in interception loss is the assumption that canopy evaporation occurs over a fraction q_C of the grid-point area.

The objective of the comparison between the different interception schemes is to explore the effects of including spatial variability in modeling of interception loss. The new scheme is compared to schemes that assume rainfall and canopy storage are constant in space and schemes that assume that rainfall is variable in space but canopy storage is constant. These comparisons reveal the *relative* effects of including rainfall variability and canopy storage variability. The results of the simulations using the off-line model are sensitive to the specified set of forcing and parameters and more importantly to the values of q_p and q_c. The purpose in using the off-line model is the *relative comparison* between the different schemes. Accurate simulation of interception loss by some of the schemes in Fig. 5 should not be taken as proof of their capability in modeling interception over large areas. This capability can only be tested by using three-dimensional climate models.

In a recent study, the new scheme is used as part of a three-dimensional model in simulations of the Amazon climate (Eltahir 1993). The scheme succeeds in predicting the partition of rainfall into interception loss and throughfall in the rainforest environment. Normalized interception loss for January and July from the model results are 0.12 and 0.14, respectively; these values are close to the estimates of 0.10 and 0.20 from the observations of Shuttleworth (1988a).

5. Conclusions

The approach of combining physical models of hydrologic processes at a point and statistical description of the subgrid-scale spatial variability is a powerful technique in deriving parameterizations of these processes for climate models. It provides useful insight into the nature of these processes over large areas.

A new interception scheme is introduced for describing interception over large areas. It combines a physical description of interception at a point, which is the Rutter model of interception, and statistical description of the spatial variability of canopy storage and rainfall. The interception loss predicted by the new scheme is significantly smaller than those predicted by other schemes that assume that canopy storage and rainfall are constant in space. This result may explain why climate models overestimate interception loss, it suggests that the neglect of spatial variability is a significant source of error in describing interception over large areas.

The interception loss simulated by the Shuttleworth scheme is slightly smaller than the losses simulated by the BATS interception or the Rutter model. Recalling that the Shuttleworth scheme treats rainfall as a spatially variable forcing, the comparison in Fig. 5 suggests that for adequate description of interception over large areas, it is necessary to include *both* the effects of spatial variability of canopy storage and rainfall.

Observations of the spatial distribution of canopy storage are not available at the scales considered in this study. Hence, the assumption about the statistical distribution of canopy storage is not supported by observations. Nevertheless, it is more reasonable to acknowledge the spatial variability in canopy storage than to assume canopy storage is constant in space.

In the above derivations, it is assumed that the distribution of canopy storage is independent from the distribution of rainfall. Since rainfall variability is the main causing factor of the variability in canopy storage, the two distributions may be related. Future research will focus on the possible effects on interception loss and canopy drainage due to the dependence of the two distributions.

The parameters of the Rutter model are assumed constant in space at the subgrid scale. The possible effects due to spatial variability in these parameters is an open question for future research. The success of the new scheme in describing interception processes over large areas depends very much on the quality of the two assumptions about the distribution of canopy storage and the variability of the model parameters.

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APPENDIX A

Interception in BATS

The BATS uses a simple description of canopy drainage. Whenever canopy storage, C, exceeds the maximum allowed storage, C_{max}, canopy drainage occurs to restore storage back to C_{max}:

$$D_r = \frac{(C - C_{max})}{\Delta t}. \quad \text{(A1)}$$

Evaporation is given by

$$e = e_c\left[\frac{C}{C_{max}}\right]^{2/3} + e_t\left\{1 - \left[\frac{C}{C_{max}}\right]^{2/3}\right\}, \quad \text{(A2)}$$

where e_t is transpiration by the plant and e_c is evaporation from wet canopy. The effects of spatial variability in rainfall or canopy storage are not included in this scheme.

APPENDIX B

Shuttleworth Interception Scheme

Shuttleworth (1988b) suggested that the effects of spatial variability on interception and runoff can be modeled by assuming rainfall, P, is exponentially distributed in space. The canopy storage, C, is assumed constant in space. This assumption is the main difference between Shuttleworth scheme and the new scheme introduced in this paper. The Shuttleworth scheme treats the spatial variability of rainfall but neglects spatial variability of canopy storage.

By making analogy between the top soil layer and canopy layer, Shuttleworth suggested that the maximum canopy "infiltration" rate is given by

$$F = \frac{(S - C)}{\Delta t}, \quad \text{(B1)}$$

where S is the amount of water retained by the canopy after being completely wet and then drained for a "sufficiently" long period.

Throughfall is then modeled by

$$T = P - F, \quad P > F$$
$$T = 0, \quad P < F, \quad \text{(B2)}$$

and the expected value of throughfall is given by

$$E(T) = \int_{P=0}^{\infty} T(P) f_P dP = E(P) e^{-[q_p \cdot F/E(P)]}, \quad \text{(B3)}$$

where f_p is the statistical distribution of precipitation defined by (5). Term q_p is the fraction of the area with $P > 0$.

The corresponding description of evaporation is not specified in Shuttleworth (1988b), for comparison purposes, it is assumed that evaporation is described by (2).

APPENDIX C

Continuity Equation in the New Scheme

The derivation of the continuity equation for the new scheme is complicated by the fact that canopy storage does not exceed the maximum storage specified as C_m. Three possible conditions are considered:

- $C \leqslant C_m$ and $0 \leqslant P < \infty$, the rate of change of storage is given by (3);
- $C > C_m$ and $(1-p)P > D_m$, the rate of change of storage is zero;
- $C > C_m$ and $(1-p)P < D_m$, the rate of change of storage is given by (3) with $D_r = D_m$.

The rate of change of the spatially averaged canopy storage is given by

$$\frac{\partial[E(C)]}{\partial t} = (1-p)\int_{P=0}^{\infty} P f_P dP \int_{C=0}^{C=C_m} f_C dC - \int_{P=0}^{\infty} f_P dP \frac{e_c}{S}\int_{C=0}^{C_m} C f_C dC - \int_{P=0}^{\infty} f_P dP \int_{C=0}^{C_m} K e^{(C/b)} f_C dC + (1-p)\int_{P=0}^{D_m/(1-p)} P f_P dP \int_{C=C_m}^{\infty} f_C dC - \int_{P=0}^{D_m/(1-p)} f_P dP \frac{e_c}{S}\int_{C=C_m}^{\infty} C f_C dC - D_m \int_{P=0}^{D_m/(1-p)} f_P dP \int_{C=C_m}^{\infty} f_C dC,$$

which is equivalent to

$$\frac{\partial(E(C))}{\partial t} = (1-p)E(P)\{1 - q_c \cdot e^{-[q_c \cdot C_m/E(C)]}\} - \frac{e_c E(C)}{S}\{1 - e^{-[q_c \cdot S/E(C)]}\} + \frac{q_c^2 \cdot K \cdot b}{[bq_c - E(C)]}\langle 1 - e^{-\{[bq_c - E(C)]C_m/bE(C)\}}\rangle + (1-p)\left\{E(P) - \left[q_P \cdot \frac{D_m}{(1-p)} - E(P) + \frac{q_P e_c}{(1-p)}\right] e^{-[q_P D_m/E(P)(1-p)]}\right\} q_c e^{-[q_c \cdot S/E(C)]} + q_P q_c (e_c + D_m) e^{-[q_P D_m/E(P)(1-p)]} e^{-[q_c C_m/E(C)]} - D_m q_c e^{-[q_c \cdot C_m/E(C)]}. \quad (C1)$$

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