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Comparison of Forest Canopy Interception Models Combined with Penman-Monteith Equation

ペンマン-モンテイス式を組み合わせた森林域降雨遮断モデルの相互比較

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Three models of interception process: Rutter model with Deardorff's power function, Deardorff model and Modified Kondo model, each in combination with Penman-Monteith equation applied to the same climatic forcing over the year of simulation were compared. The modification of the Kondo's model done in our study includes the water balance component, between storms evaporation and transpiration including the power function, storage changes and the canopy drainage. The comparison was meant for assessing the simple Modified Kondo model developed in Japan and demonstration of the importance of the power function. The Penman-Monteith equation was the kernel for determination of evaporation and transpiration rates. Its use in this study was proposed because it has been widely used in Japan and in experimental sites and therefore can be used as a basis for comparison. Since much interest was on net rainfall, the control volume for the water accounting was between top of the canopy and above the ground surface and hence does not include soil moisture and transpiration. Results showed that forest canopy evaporation ranged from 22 to 29% of gross rainfall. Much model prediction differences were observed in winter, with lower rainfall intensity where wet canopy storages or rainfall did not meet the potential (atmospheric) evaporation demand. The annual net rainfall and transpiration ranged from 71 to 78% of gross rainfall and from 727 to 733 mm respectively. The adopted power function had significant impact on transpiration rate and small impact on evaporation rate for the Modified Kondo model. The Modified Kondo model predicted fairly close to the two models and therefore can be used for providing hourly input into hydrological models. The differences in the predicted hydrological fluxes resulted from the different model formulations especially throughfall coefficients and drainage functions.

Key words: Penman-Monteith equation, Closed forest canopy, LAI, Evaporation, Transpiration, Canopy water balance, Hikimi River basin, Japan

降雨遮断に対する三種類のモデル(Deardorff のべき関数式を用いたRutterのモデル, Deardorffのモデル, 修正近藤モデル)に気象外力を与えて一年間のシミュレーションを行い, その結果を比較した。それぞれの降雨遮断のモデルには, ペンマン-モンテイス式を組み合わせた。修正近藤モデルは, 水収支を構成する種々の要素を考慮したものであり, 降雨イベント間の蒸発散機構も取り入れられている。この蒸発散の計算には, Deardorffのべき関数式, キャンピでの貯留量の変化, キャンピからの流出が考慮されている。ペンマン-モンテイス式は蒸発散量を決定するうえで核となる部分である。この式は日本あるいは試験流域で広く適用されており, 本研究においても, 降雨遮断モデルの比較の基礎として用いることにした。本研究では有効降雨に着目していることから, 水収支のコントロールボリュームはキャンピの上端から地表面までの間としており, 水収支の計算には土壌水分量や蒸散量は含まれていない。モデルの計算結果から, 森林キャンピからの蒸発量は全降水量の22%から29%となることが明らかとなり, また, モデル間の差異は冬季の計算で大きくなることも明らかとなった。冬季は降水量が少なく, キャンピの貯留量や降水量がポテンシャル蒸発量を満たさなくなるために, モデル間の違いがはっきり現れたものと考えられる。年間の有効降水量は総降水量の71%から78%, 年間の蒸散量は727mmから733mm程度と算定された。また, 修正近藤モデルにべき関数式を適用し

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たところ、蒸散量の値には大きな影響が、蒸発量の値には若干の影響が見られた。修正近藤モデルによる計算結果は他の二つのモデルの結果とほぼ同等であり、水文モデルに対する時間単位の入力を算出するために使用できると考えられる。モデル間の蒸発散量の違いは、主として樹冠通過率と貯留量流出量関係の定式化の違いから生じている。

キーワード：ペンマンンモンティース式、閉塞した森林キャノピー、LAI、蒸発、蒸散、キャノピーでの水収支、匹見川流域

I. INTRODUCTION

Precipitation and evapotranspiration are two important processes to the fields of hydrology and meteorology. Precipitation studies are dealt at length in meteorology. The combined process of evaporation and transpiration from vegetated land surfaces is referred to as evapotranspiration. Precipitation is the primary input of water to a catchment. Precipitation stored by the canopy or leaf litter is known as canopy interception and may evaporate and/or drain. The capacity of the canopy and litter to store water is limited, and the rain interception and snow interception capacities are not the same value. Precipitation that is not intercepted by the canopy is known as throughfall. The one that leaves the temporary storage of interception or along the tree trunk may be classified as either drainage (runoff) or stem flow. Other definitions of throughfall may include the water that reaches the ground directly or by dripping off leaves. This partitioning of precipitation between vegetated surfaces and the soil is crucial in defining the storages of water available for direct evaporation from surfaces and for transpiration by plants of water taken up from the soil through roots. In short, the forest canopy storage is filled by the precipitation and discharged by evaporation and drainage. Evaporation can be substantial for catchments densely covered with trees (e.g. Rutter, 1971). Moreover, the evaporation from wet leaves in a forest can be much faster than from a water surface exposed to the same meteorological conditions (Stewart, 1977).

Evapotranspiration is often the primary output of water from a catchment. Evapotranspiration depends mostly on the properties of the land surface and the state of the near surface air and is therefore dwell within the domain of hydrology. The

main concern has been rates, timing, and spatial distribution of water fluxes between the land and the atmosphere. In this paper, we explored the models of the process of forest canopy interception, which are core to calculation of evapotranspiration flux from the catchment and play a significant role on hydrological modeling and land surface-atmosphere interactions. The aim of the study was not to determine which model is the best but relative predictability and to see the extent to which the newly Modified Kondo model developed in this study, can provide evaporation, net rainfall and transpiration estimates that compare with those of widely used Deardorff and Rutter models in land surface parameterization schemes. The canopy drainage and throughfall are referred to as net rainfall and is used as an input to hydrological models. Evaporation reduces water amount available for drainage and together with transpiration, are outputs from the hydrological model.

Mizutani, *et al.* (1997) emphasized the importance of partial cover in the determination of evaporation and hence transpiration, therefore this study demonstrates the usefulness of the power function in canopy interception models. The partial cover is part of the water balance and therefore affects canopy drainage and transpiration. Murakami, *et al.* (2000) used the Kondo model in an event time step on daily climatic forcing without the power function and considered no transpiration during rainfall. Therefore, to enhance the accuracy of hydrological models for small time steps (hourly) to capture the rainfall events and flood peaks, accurate canopy drainage and transpiration is essential. For these purposes, the power function was adopted and we evaluated its impacts on the Modified Kondo model. Also, to assess the prediction of each model for hydrological model input, comparison of three models for long-

term simulation of hourly evaporation and transpiration rates from a closed forest canopy is presented. Focus was on dense forests, which are widely found in Japan.

Various models of interception exist such as analytical models (e.g. Gash, 1979), numerical models (e.g. Mulder, 1985; Whitehead and Kelliher, 1991), stochastic models (e.g. Calder, 1977 & 1986), probabilistic models (e.g. Kondo *et al.*, 1992), physically based (e.g. Rutter *et al.*, 1971/75) and conceptual models (e.g. Deardorff, 1978). In this study, three models of interception process (Rutter *et al.*, 1971/75 with Deardorff (1978) fractional cover equation; Deardorff (1978); Modified Kondo, *et al.*, 1992) in combination with the Penman-Monteith equation (PM) applied to the same climatic forcing over the years of simulation were compared. This was achieved by running a pair of the models (PM model and one interception model) with the same data set thereby enabled comparison of the different combinations while minimizing the differences in the kernel for evaporation and transpiration determination. The three models will be referred to as Deardorff, Rutter and Modified Kondo models respectively. The Rutter and Deardorff models are famous in land surface parameterization schemes (e.g. SHE and, ISBA and SiB respectively). Analyses assessed the relative performance of combination of the PM model and each of the three interception models. Moreover, a model with comparable results with that of the Rutter model which can be considered as a reference for rainfall interception (Noilhan and Mahfouf, 1996) may be considered the best of the two. Also, some reference was made to compare the interception model results with other studies that used PM or similar/comparable models in Japan for computing the surface energy balance and consequently forest evaporation and transpiration.

II. THE PENMAN-MONTEITH EQUATION

The Penman-Monteith equation (Eq. 1) (Monteith, 1965) is a basic formula used in simple, one-dimensional single source description of the eva-

potranspiration process. When the source of water vapor is a completely wet vegetation canopy, the term r_c is zero and the equation reduces to Penman equation so that the resultant expression gives the rate of evaporation of intercepted water.

$$\rho_w \lambda E = \frac{\Delta (R_n - G) + \rho_a c_p (e_s(T_a) - e(T_a)) / r_a}{\Delta + \gamma (1 + r_c / r_a)} \quad (1)$$

Where ρ_w is the density of water [kgm^{-3}], E is the water vapor flux [ms^{-1}], Δ is the slope of the saturated specific humidity-temperature curve [kPaK^{-1}], R_n is the net radiation [Wm^{-2}] determined using energy balance method (Brutsaert, 1982) with 0.98 as a surface emissivity for upward long wave irradiance for vegetation, G is the soil heat flux [Wm^{-2}] assumed to be zero because the bulk of the canopy is over 10 m above ground, ρ_a the air density [kgm^{-3}] calculated using air pressure, c_p the specific heat at constant pressure [$\text{Jkg}^{-1}\text{K}^{-1}$], e_s the saturated vapor pressure [kPa], e the vapor pressure [kPa], T_a the air temperature [K], r_a the aerodynamic resistance [sm^{-1}], r_c the canopy resistance [sm^{-1}], γ the psychrometric constant [kPa K^{-1}] and λ the latent heat of vaporization [Jkg^{-1}]. The equation requires solar radiation, air temperature, wind speed, and relative humidity as inputs. The upward long-wave radiation was calculated by Stefan-Boltzman's law with canopy surface temperature assumed equal to air temperature measured at 1.5 m. Brutsaert (1982) indicated that since surface temperature is rarely known, especially over land, air temperature is often used instead of surface temperature in determination of upward long-wave radiation. This simplification was assumed in this study and extended to the canopy surface. The downward long-wave radiation was estimated from air temperature, Stefan-Boltzman's constant, relative humidity and atmospheric emissivity by Satterlund, which includes both temperature and atmospheric humidity effects (Brutsaert, 1982). The albedo used was 0.1 (Brutsaert (1982); Biftu and Gan (2001) and Murakami *et al.* (2000)).

The aerodynamic resistance, r_a is estimated using the logarithmic boundary layer equation in neutral conditions.

Table 1 Some evapotranspiration and canopy interception estimation studies in Japan

No.	Year	E_c (mm)	E_t (mm)	E_{ct} (mm)	Method	Site	Publication
1.	1993	234	613	847	SVATs for forest area on daily basis	Central-Southern Japan (around Mt. Fuji)	1999 (5)
	1992	213	658	871			
	1991	242	627	869			
	1990	235	666	901			
2.	1996			736.7 (forest)	Thornthwaite	Tohoku	1996 (4)
	1993			526.6	Morton (monthly)	Hokkaido	
	1993			450.1	Complementary rel. of Penman & PT		
3.	1990/91	316.7	581.5	898.2	PM (forest)	Southern part of Shiga prefecture	1995 (2)
	1986/87			778.42	PM & Calder		1990 (3)
	1986/87			912.38	Penman (Potential rate)		1990 (3)
	1986/87			778.81	Hamon-Daily (Potential rate)		
	1986/87			764.2	Thornthwaite		
4.	1981/85	515	333		PM on monthly basis	Hitachi Ohta on the Pacific coast of Eastern Japan	2000 (1)

Note: SVATs is a Soil-Vegetation-Atmosphere-Transfer scheme, c is canopy evaporation, t is transpiration, ct is evapotranspiration, PM is Penman-Monteith equation, PT is Priestly-Taylor & Calder is the interception model (Calder, 1977). Under the Publication, the numbers in the bracket refer to the references cited in the text below for Table 1.

$$r_a = \frac{1}{\kappa^2 u} \left[\ln \left(\frac{z_h - z_d}{z_o} \right) \right]^2 \quad (2)$$

Where κ ($=0.4$) is von Karman's constant, u [ms^{-1}] the wind speed at the reference height z_r , z_h [m] the zero plane displacement and z_o [m] is the roughness length. The relation $z_d = 0.78h$ and $z_o = 0.07h$ (h is the average forest height) was used. For the forest in this study, it is assumed that $z_h = h = 20$ m giving $r_a = 8.2/u$, where u was measured at a height of 10 m such that equals the basin average speed at the top of the canopy. The stability conditions were assumed to be neutral, which Shuttleworth (1989) found to be satisfactory over forests. For the transpiration, the canopy resistance (r_c) was estimated by Calder (1977) that is associated with changing environmental variables but not including soil moisture as most Japanese forests may satisfy this condition, and is given by:

$$r_c = \frac{C [1 - A \cos(2\pi(D - 222)/365)]}{1 - B \delta e} \quad (3)$$

Where the constants A , B , and C are determined by observation but in this study reported values by Murakami, *et al.* (2000) were used: $A = 0.37$, $B = 0.036 \text{ hPa}^{-1}$, and $C = 130 \text{ sm}^{-1}$. δe [hPa] and D is the vapor pressure deficit and the Julian day respectively.

The use of PM in this study was proposed due

to the fact that it has been widely used in Japan and in experimental sites and therefore can be used as a basis for comparison. Also, the same evaporation and transpiration kernel is used to minimize the differences due to the different model formulations. Some of the studies that used PM or energy balance method whose summary of results is presented in Table 1 are: (1) Murakami, *et al.* (2000); (2) Mizutani and Ikeda (1995); (3) Rampisela, *et al.* (1990); (4) Tada, *et al.* (1996); (5) Yao and Terakawa (1999). Table 1 shows the range of evaporation, transpiration and evapotranspiration estimated in various areas in Japan and can also shade light to improvements relative to this study.

III. MODELING OF CANOPY INTERCEPTION

The compared models use similar relationship in the determination of potential evaporation and transpiration, but differ in formulation and complexity: Rutter—physically based and complex, Deardorff—conceptual and simple, and Modified Kondo—with probabilistic properties and relatively simple.

The term Kondo and Modified Kondo model will be used interchangeably to refer to the Modified

Kondo model in this study. All models track down the storage changes in the canopy of the water remained after a rainfall event at each time step till the next rainfall event. The Kondo model was modified to include the decrease of evaporation rates of intercepted water with decreasing canopy storage and increase of transpiration between storms, and canopy drainage. Unlike the other two models, the Kondo model has an equation for remaining canopy storage at each time step for the higher rainfall intensity at that time, implying that evaporation is abstracted from rainfall rather than storage but between storms the storage is used. Also, only the Rutter model has an explicit equation for the drainage. The canopy can retain only a certain amount of rainfall, the so-called maximum storage capacity S_{max} . Some models assume that when stored rain exceeds S_{max} , excessive water runs off to the ground. Others consider runoff from the canopy to occur even if S_{max} is not reached (e.g. Rutter and Modified Kondo models). For the models, the initial storage was set to zero. In all interception models, stem flow is neglected.

The models were analyzed for evaporation and transpiration prediction for dense mixed forest, which are dominant Japanese forests. The typical forest in Hikimi River Basin is Japanese cedar (*Cryptomeria japonica*), Japanese cypress (*Chamaecyparis obtuse*) and Japanese beech. A critical parameter in the interception models is the Leaf Area Index (LAI) and probably portions of the canopy that are dry or wet. The value of LAI used was 5.6 (Murakami, *et al.*, 2000). In this study, concentration was on net rainfall as input to hydrological models, thus the control volume for the water balance was between top of the canopy and above the ground surface and does not include soil moisture and transpiration. For a complete water balance, soil moisture and transpiration has to be included.

The description of each of the interception models follows below:

1. Deardorff Model

Following Deardorff (1978), interception is mod-

eled by considering the canopy as a bucket, which is filled by precipitation and emptied by evaporation and runoff. The bucket flows over if S_{max} is reached. Assuming a closed canopy that intercepts all raindrops, variations in storage S are calculated by the canopy water balance as:

$$\frac{\partial S}{\partial t} = vegP - E_c - R \quad \text{for } 0 \leq S \leq S_{max} \quad (4)$$

Where; veg is the degree of canopy closure, P is the precipitation flux, E_c is the evaporation flux from the wet canopy (Eq. 6), and R is the drainage function from the canopy, all in mmhr^{-1} . The value of veg used is 1. S is the bucket water content. Runoff occurs only if S exceeds S_{max} . The value of S_{max} in mm of water is evaluated from the vegetation index using Dickinson (1984)'s equation for a closed canopy as:

$$S_{max} = 0.2 LAI \quad (5)$$

The wet canopy evaporation flux is evaluated as:

$$E_c \Delta t = \min(S, \omega E_o \Delta t) \quad (6)$$

Where E_o is the rate of evaporation from the entire wet canopy given by solving Eq. 1 with r_c equal to zero. Δt is the time step (an hour) of the simulation. The transpiration rate from the dry canopy is obtained as:

$$E_r = (1 - \omega) E_p \quad (7)$$

Where E_p is the transpiration rate obtained from Eq. 1 and ω is the area fraction of wet canopy also known as power function, which is determined as:

$$\omega = \left(\frac{S}{S_{max}}\right)^{2/3} \quad (8)$$

This fractional power is specified to allow the canopy water to evaporate more rapidly with the water occupying only fraction of the leaf area during evaporation and the entire area during condensation ($\omega = 1$). Moreover, the stored water hinders transpiration that is relevant to models of forest water use and growth.

2. Rutter Model

The Rutter Model is used in combination with the power function of Deardorff (1978). The canopy water balance is described by:

$$\frac{dS}{dt} = (1 - \delta)P - E_c - R \quad \text{for } 0 \leq S \leq S_{max} \quad (9)$$

Where P is the precipitation flux, δ is the free throughfall coefficient (the proportion of rain which falls to the ground without striking the canopy) determined by Eq. 11, E_c is the wet canopy evaporation flux determined using Eqs. 6 to 8 but transpiration by Eq. 7 and R is the drainage function given by Eq. 10.

$$R = k \exp[-b(S_{max} - S)] \quad (10)$$

Where k and b are Rutter's drainage parameters, S_{max} is the canopy water storage capacity (Eq. 5) and S is the actual amount of water intercepted by canopy. A value of b for forest vegetation used is 4.6 mm^{-1} selected out of the range $3.0 - 4.6$ (Rutter *et al.*, 1975).

Based on past measurements of δ and LAI , a simple regression was established by Biftu and Gan (2001) to convert LAI to δ . The obtained linear relationship of δ and LAI for different types of vegetation is:

$$\delta = 0.997 - 0.139 LAI \quad (11)$$

Rutter *et al.* (1975) estimated the drainage parameter k for any vegetation canopy as:

$$k = 0.0019 S_{max} \quad (12)$$

3. Modified Kondo model

The canopy interception model by Kondo, *et al.* (1992) as cited by Murakami, *et al.* (2000) was modified in this study to compute evaporation and transpiration more realistically depending on conditions (day or night and/or during rainfall), on hourly basis and availability of water for evaporation. In the earlier version, during rainfall it was considered that no transpiration even if the canopy storage is not entirely wet. The modifications included the water balance component, between storms evaporation and transpiration including the power function (Eq. 8), storage changes and canopy drainage. When the time between the storms is too short to dry the canopy completely, the water left in the canopy after the storm is taken into account in the next storm. Otherwise, water left on canopy evaporates and on the dry part, transpiration takes place. The fractional wet and

dry canopy cover was considered (Eq. 8) to compute evaporation and transpiration.

The canopy water balance is described by:

$$R(t) = veg^* P(t) - E_c^*(t) - [(S(t) - S(t-1)) / \Delta t] \quad (13)$$

Where; veg^* is the chance of the raindrop hitting the canopy (Eq. 17), $P(t)$ is the precipitation flux, $E_c^*(t)$ is the evaporation flux from the wet canopy with and without distinguishing the dry and wet (Eqs. 6 & 7) parts (without distinguishing meant only E_c occurred and equal to $\min(E_c, S(t-1))$ and no transpiration during rainfall), and $R(t)$ is the drainage function from the canopy, all quantities in mmhr^{-1} . The runoff occurs only as a result of the running water balance when the rainfall intensity is higher, the case of Eq. 16 or because of accumulative storage during the low rainfall intensity, the case of Eq. 15. $S(t-1)$ is the water storage at time $t-1$ (previous time storage). $S(t)$ is the canopy water storage remaining due to the current time step rainfall and is given by Eq. 14. Δt is the time step (an hour) of the simulation.

$$S(t) = S_{max} [1 - \exp(-P(t) \Delta t / S_{max})] \quad (14)$$

Where Eq. 5 obtained S_{max} . Eq. 1 determined the evaporation of intercepted water and transpired water similarly but the difference lies on the differences of the canopy resistances, which is equal to zero for the former.

When the interception I , is from a low intensity rainfall, evaporation rate from the canopy is larger than the capture rate of raindrops (all the rain-water caught by the canopy evaporates) given by Eq. 15. The exception is when $veg^* P(t)$ exceeds $E_o(t)$ where $S(t)$ becomes the difference of the two and runoff is the balance.

$$I = veg^* P(t) \Delta t \quad \text{if } veg^* P(t) \Delta t < E_o(t) \Delta t + S_{max} \quad (15)$$

During a high intensity rainfall canopy interception I , consist of three components: evaporation from the wet surface during rainfall, evaporation from the residual water on the canopy after the rainfall and the canopy drainage, $R(t)$ as:

$$I = E_o(t) \Delta t + S(t) + R(t) \Delta t \quad \text{if } veg^* P(t) \Delta t \geq E_o(t) \Delta t + S_{max} \quad (16)$$

Where $S(t)$ is given by Eq. 14 and veg^* , the

chance of the raindrop hitting the canopy is given as:

$$veg^* = veg [1 - \exp(-F * LAI / veg)] \quad (17)$$

Where *veg* is the degree of canopy closure ($0 < veg \leq 1$, $veg = 1$ for closed canopy), *F* is the leaf inclination factor corresponding to randomly oriented leaves, assumed constant ($=0.5$) (Murakami, et al., 2000).

IV. CLIMATIC CHARACTERISTICS OF THE STUDY AREA

The Hikimi River basin of basin area of about 352 sq. km. is located in Shimane Prefecture, southwest of Japan near the Japan seacoast and mainly covered by closed forest canopy. Hourly climate data at Hamada weather observation station was used in this study. Rainfall provided water input to the forest canopy. Based on the 1991–1995 data, the distribution of the rainfall data for monthly averages and annually is shown in Figs. 1 and 2 respectively. Maximum and minimum rainfall occurred in the months of July and October respectively. The annual average rainfall is about 1600 mm. The years 1992 and 1994 were below the average and may imply a dry spell where canopy evaporation or transpiration could be significant. Canopy interception and transpiration simulations were done for the year 1994. The year had 231 rainfall events separated by 6 hours without rainfall; the longest event is 18 hours of rainfall; the maximum storm size is 44.5 mm that occurred in 15 hours of rainfall and the heaviest storm had an intensity of 10 mm that occurred in 1 hour of rainfall. The storm rainfall intensities ranged 0.5–10 mm/hr, the standard deviation was 1.46 mm/hr and the average rainfall intensity for all storms was 1.43 mm/hr. Other meteorological data used were; solar radiation, air temperature, wind speed, water vapor pressure deficit (derived from relative humidity) and air pressure. The seasonal hourly means for these variables are shown in Fig. 3 along with the seasonal hourly net radiation flux, which peaks at 12 and 13 hours. In most cases, high meteorological variations occurred between hours 8 and 18 during the day.

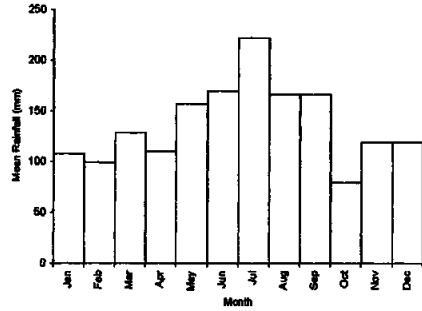


Fig. 1 Seasonal rainfall for the year 1991–1995

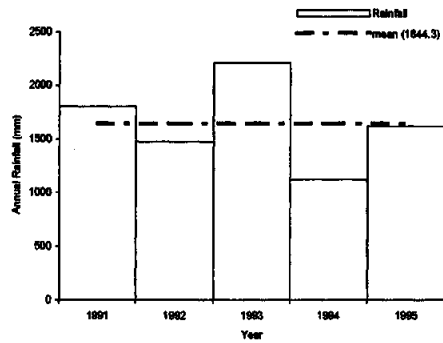


Fig. 2 Rainfall variation for the years 1991–1995

V. SIMULATION RESULTS AND ANALYSIS

1. Models predictions

The hourly evaporation and potential transpiration rate for the models were calculated using the canopy storage capacity of Eq. 5 and hourly meteorological data. In this case, S_{max} becomes 1.12 mm. Fig. 4 shows the hourly seasonal distribution of the models' canopy evaporation and gross rainfall for the year 1994. The year was grouped roughly into four seasons: Winter from Jan. to Mar.; Spring from Apr. to Jun.; Summer from Jul. to Sep.; Autumn from Oct. to Dec. Hourly mean values were calculated for non-zero values of rainfall and evaporation.

From the hourly distribution, all models showed more or less the same pattern of the evaporation. The mean values of the season's rainfall and evaporation rate (non-zeros) for the models were respectively: 1.341mm/hr and 0.326mm/hr in

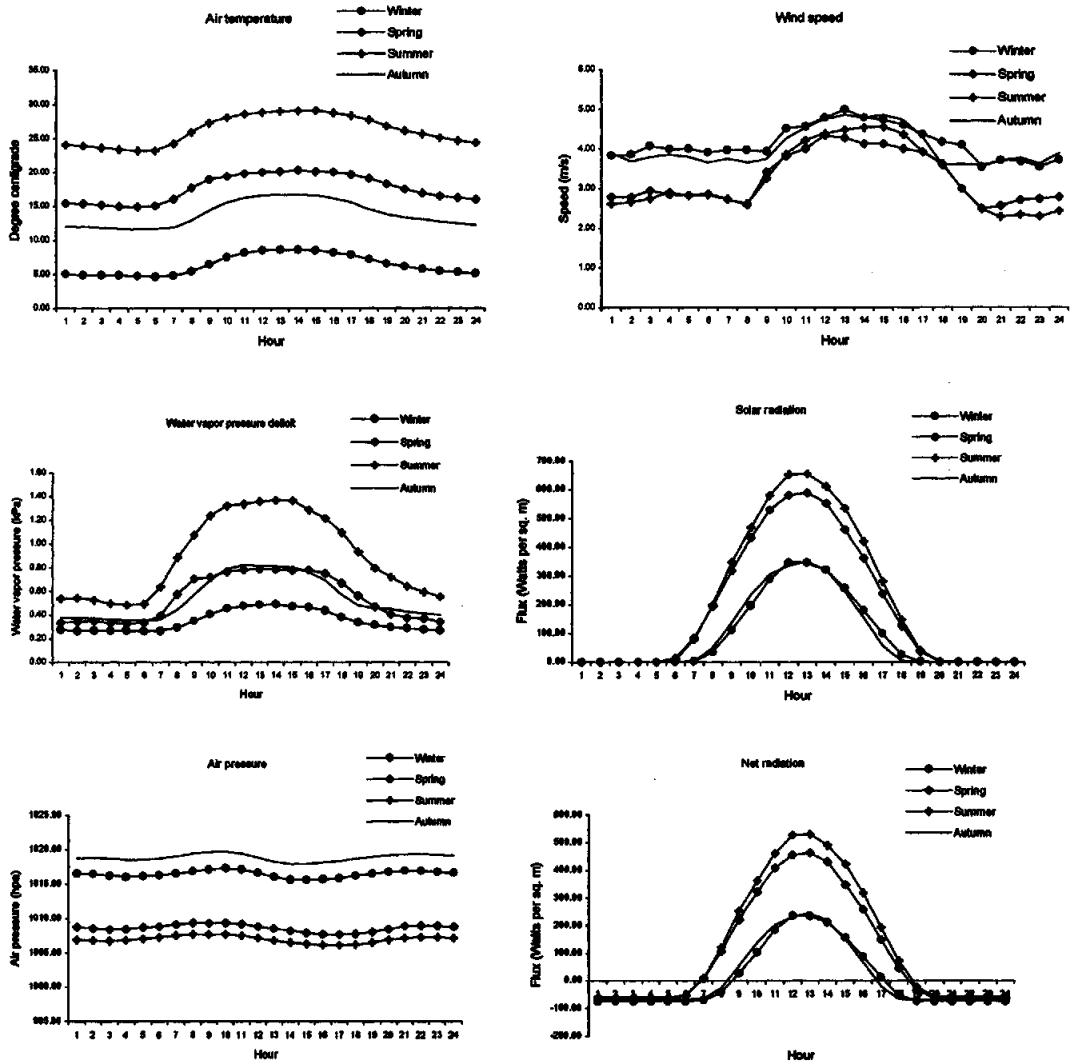


Fig. 3 Seasonal hourly mean of meteorological variables and net energy flux

winter; 1.728mm/hr and 0.168mm/hr in spring; 2.400mm/hr and 0.385mm/hr in summer and 1.819mm/hr and 0.347mm/hr in autumn. The Kondo model's mean values for the seasons were respectively: 0.346, 0.183, 0.428 and 0.412. Standard deviation for mean rainfall in the seasons was respectively: 0.396, 0.688, 1.330 and 1.360. The evaporation flux depend on whether is day or night and the state of meteorological variables including the intensity of rainfall. Low values are during the night and low rainfall intensity while high values are during the day and high rainfall

intensity. As a result, higher evaporation rates occurred in summer because of the highest rainfall, water vapor pressure deficit, air temperature and net radiation, and lower evaporation rates occurred in spring because of lower wind speed, water vapor pressure deficit and low air pressure (Figs. 3 & 4). The figures show that differences between summer and spring is due to the differences in water vapor pressure deficits and therefore water vapor pressure deficit had a major control on the extreme evaporation rates. Mizutani, *et al.* (1997) obtained mean evaporation of 0.371mm/

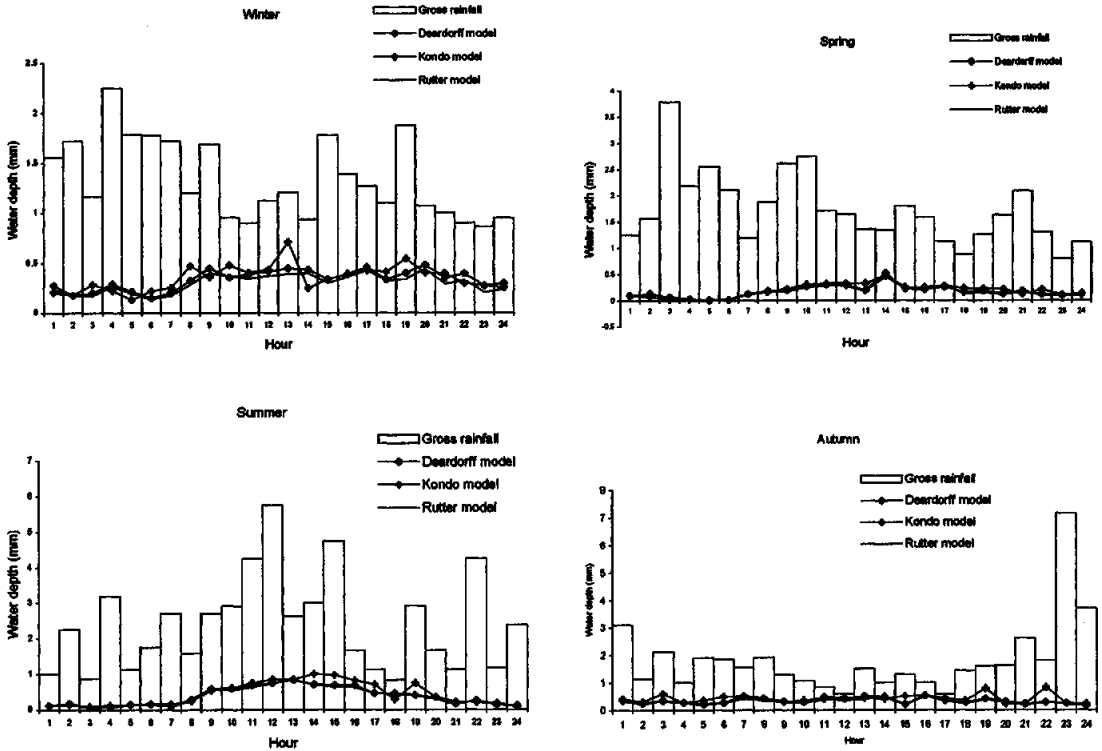


Fig. 4 Seasonal hourly mean canopy evaporation for the models

hr when the mean rainfall intensity was 1.75mm/hr by eddy correlation/energy balance method and reported almost same results with the PM. Calder and Wright (1986) showed that when the mean rainfall intensity was about 2.400mm/hr, the mean evaporation intensity was about 0.409 mm/hr. These rates correspond respectively to the obtained autumn and summer fluxes and therefore the values in this study are within the expected ranges.

Uniform evaporation distribution is in spring and summer because of slight variation of meteorological variables (e.g. water vapor pressure deficit, wind speed, air pressure and high rainfall) and energy flux in these times of the year (Figs. 3 & 4). Though the rainfall standard deviations were relatively high, net radiation and water vapor pressure deficit influenced much and in most cases wet canopy storages or rainfall satisfied the potential (atmospheric) evaporation rate of the kernel. Higher variation of evaporation is in winter and

slightly in autumn because of slight diurnal variation of meteorological variables (wind speed and air pressure), energy flux and low rainfall in these seasons (Figs. 3 & 4), where wet canopy storages or rainfall did not meet the potential (atmospheric) evaporation demand. Also, in winter and autumn, at night wind speed variation (also in magnitude) is higher compared to water vapor pressure deficit variations in other seasons. These results agree with Mizutani, *et al.* (1997) who observed that PM is too sensitive to the wind speed and vapor pressure deficit. The Kondo model had sharp variations due to the switch from Eq. 15 for $\min(veg * P(t), E_c(t))$ to Eq. 16 for $E_c(t)$. On average, the Kondo showed higher evaporation rates because some rainfall hours, which satisfies Eq. 15 and all evaporated, while for other models will be subject to evaporation and/or drainage. The Rutter model showed the lowest evaporation rates of the three but nearly had same evaporation rate like the Deardorff model on hourly averages.

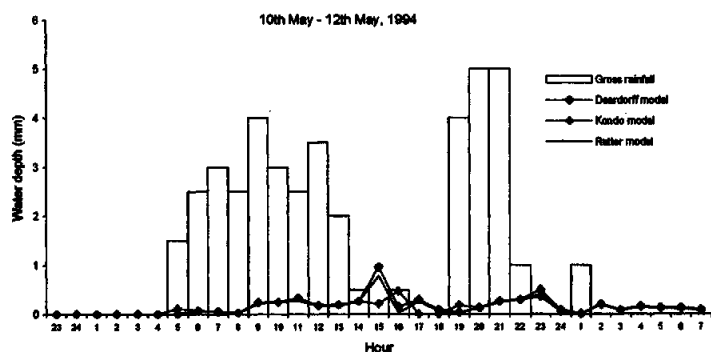


Fig. 5 Comparison of hourly simulation of canopy evaporation of an event by the models

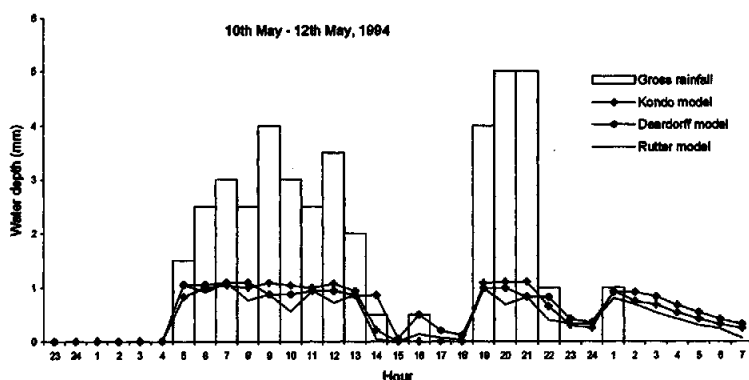


Fig. 6 Comparison of hourly simulation of canopy storage of an event by the models

For a refined illustration of temporal distributed prediction of the models, a rainfall event at early summer, from 10th May at 23 hours to 12th May at 7 hours was selected as presented in Fig. 5.

Fig. 5 shows that the Deardorff model predicted close to Rutter model. Overall, evaporation predictions are more or less the same for the models except at the hour 15 and, slightly at hours 17, where the Kondo model's is lowest of the three. Low evaporation resulted from the lowest storage during no rainfall and recession. It seemed that the models drained much towards the end of event and therefore little water was available for evaporation.

Fig. 6 shows the end of hour storages along with the rainfall amount. Fig. 6 together with Fig. 5 shows a decrease of evaporation rates of intercepted water with decreasing canopy storage be-

tween storms as evidenced by Shuttleworth (1977); Calder and Wright (1986). During rainfall the storages were maintained nearly the maximum storages.

Table 2 shows the annual values for the 1994 hourly simulation and the rainfall accounting. The remaining storage is the storage at the end of the simulation. The mismatch of the model output and rainfall input is expressed in percentage and may imply a model error. All percentages are out of the gross rainfall. Results showed that annual forest canopy evaporation ranged from 249 to 330 mm (22 to 29% of gross rainfall). The results in this study are very close to the SVATs model results for the central-southern Japan study in Table 1. Kondo, *et al.* (1992) reported the amount of interception loss to be about 20% of the annual rainfall amount in Japan. The results in this study are

Table 2 Annual Evaporation, water balance and transpiration for the year 1994

Water variable	PM/Kondo	PM/Deardorff	PM/Rutter
Transpiration	733.487	727.208	728.708
Canopy evaporation	329.848	279.140	249.426
Intercepted rainfall	1056.590	1125	879.075
Evapotranspiration	1063.335	1006.348	978.134
Throughfall	68.411	0.000	245.925
Canopy drainage	726.741	845.860	629.649
Net rainfall	795.152	845.860	875.574
Net rainfall/gross rainfall, %	70.680	75.188	77.829
Evap./gross rainfall, %	29.320	24.812	22.171
Remaining storage, %	0.000	0.000	0.000
Output-input mismatch, %	0.000	0.000	0.000

Table 3 S_{max} and ω sensitivity analyses for the Modified Kondo model

Water variable	PM/Kondo		PM/Kondo	
	$S_{max} = 0.98$ mm Without power function	$S_{max} = 0.98$ mm With power function	$S_{max} = 1.12$ mm Without power function	$S_{max} = 1.12$ mm With power function
Transpiration	476.239	733.327	476.189	733.487
Canopy evaporation	288.161	326.996	289.710	329.848
Intercepted rainfall	1056.590	1056.590	1056.590	1056.590
Evapotranspiration	764.400	1060.323	765.899	1063.335
Throughfall	68.411	68.411	68.411	68.411
Canopy drainage	768.428	729.593	766.878	726.741
Net rainfall	836.839	798.004	835.290	795.152
Net rainfall/gross rainfall, %	74.386	70.934	74.248	70.680
Evap./gross rainfall, %	25.614	29.066	25.752	29.320
Remaining storage, %	0.000	0.000	0.000	0.000
Output-input mismatch, %	0.000	0.000	0.000	0.000

close to the reported values and the slight difference could be due to the details of the process and data input. The Kondo model produced highest values of annual evaporation because during rainfall, evaporation is abstracted from rainfall before reaching the storage and consequently highest transpiration. The Kondo model had 426 rainfall hours out of 672 total rainfall hours for the year, which satisfies Eq. 15 and evaporated. All rainfall for these hours was considered to be intercepted by Deardorff model and some amount by Rutter model and will be subject to evaporation and/or drainage. Therefore, it is expected that the evaporation of Kondo model to be higher than that of other models for the same rainfall intensities. Once evaporated, the canopy becomes dry or partly dry and hence higher transpiration rate. Due to accumulated storage and drainage not allowed below S_{max} higher evaporation rates are expected for the Deardorff model than the Rutter model.

The annual transpiration ranged from 727 to 733 mm and may indicate the assumed potential rates. The Kondo model had highest transpiration of the three. The annual net rainfall ranged from 71 to 78% of gross rainfall. Net rainfall is greater for Rutter model followed by Deardorff model and last Kondo model. Therefore, more input to the hydrological model is expected for the Rutter model compared to others but the Kondo model's input nears that of the two models. The effect on the Modified Kondo model with and without fractional cover/power function, and sensitivity of S_{max} is shown in Table 3.

The model differences in prediction versus the Rutter model are probably the differences in the models formulation. The models have different treatment of throughfall coefficients and drainage functions. For the throughfall, with the set $veg=1$, the Deardorff model assumed that all gross rainfall (100%) is intercepted by forest canopy and the

Kondo model gives 93.92% of the gross rainfall by Eq. 15 or 16 is intercepted. While the Rutter model gives 78.14% of the gross rainfall is intercepted as given by a fraction 1 minus value of Eq. 11. Although the models used same storage capacities, have different amounts of intercepted rainfall because of their differences in throughfall coefficients. This affected the amount of water available on the storage for evaporation and transpiration through the power function and consequently the canopy drainage.

As for the drainage function differences, the Deardorff model drainage exists when the canopy storage capacity is exceeded. During higher rainfall intensities, higher drainage is expected for the Deardorff model than the Rutter model, which has maximum drainage when $S=S_{max}$ and continuing rain will become free throughfall. In the Rutter model drainage function (Eq. 10 & 12) a value of b out of the provided range was assumed and probably could have effect on the amount draining at any time at the study site. In this study, we avoided the inherent weakness in the Rutter drainage function of predicting a finite drainage when the canopy is dry by constraining the drainage to zero. The Kondo model had the lowest drainage because of highest evaporation rates although it kept well tracking the changes is storage like other models. The differences in drainages are also caused by the amount of intercepted water, which is different for each model based on its formulation.

2. Sensitivity analysis for the Modified Kondo model

Cases without and with the power function intended to assess the power function impacts on the Modified Kondo model (Table 3). Without the power function looked like the method used by Murakami, *et al.*, 2000, which considered two cases; day and no rainfall (there's transpiration but no evaporation), and with rainfall (there's evaporation but no transpiration) but in this study traced water on the storage. With the power function, at any time (with no rainfall and during rainfall times

distinguished) traced water on the storage and contributions from wet or dry calculated. $S_{max}=0.98$ mm obtained by measurement (Murakami, *et al.*, 2000) was used for the case without and with the power function in order to compare the Modified Kondo model with the study of Hitachi Ohta in Table 1 as in other studies, S_{max} was not stated or differed from this earmarked, and when S_{max} is given by Eq. 5.

From Table 3, the Kondo model results without considering the canopy fractional cover gave 476.189mm/y transpiration but considering the canopy fractional cover gave an increase of 257.298 mm/y (54.033%). The corresponding percentages for evaporation were 25.752% and 29.320% respectively, the latter being an increase of only 3.568%. The fractional cover, which is wet and dry by Deardorff (1978), seemed to have significant effect on transpiration but not to the evaporation. Nearly same effects were observed when $S_{max}=0.98$ mm. This shows that for the Kondo model the fractional cover is more important for transpiration than for evaporation, because a large part the canopy may be dry in most cases especially for low intensity rainfall hours/event that evaporated. All the three models had more or less same transpiration rates because the differences in throughfall coefficient, canopy storage capacity and drainage functions had small influence on transpiration rates.

As for the storage capacity values (Table 3), using S_{max} by Eq. 5 and 0.98 mm showed insignificant effects in evaporation and transpiration fluxes, implying a storage capacity or LAI decrease of 12.5% had no effect on the water fluxes for the Kondo model. Comparison with other studies in Table 1, particularly the study in Hitachi Ohta on the Pacific coast of Eastern Japan that used the Kondo model and $S_{max}=0.98$ mm, showed quite different rates for the case without the power function. Much impact was observed when the power function was adopted, in which there were higher and lower evaporation and transpiration respectively than in this study. The reason is large time step (event) on daily meteorological inputs, which

did not catch the hourly variation and the assumption that no transpiration during rainfall and partial cover, and evaporation was considered only during rainfall.

VI. CONCLUSION

The three models: a physically based Rutter model, a conceptual Deardorff model and a slightly probabilistic Kondo model were applied to a set of rainfall and climatic data for the dense forested Hikimi river basin to explore the predictability of the famous types of interception models for land surface parameterization relative to the Kondo model formulated in Japan. The main formulation difference of two models from the Rutter model is that the two has no equation for canopy drainage. Also, unlike the other two models, the Kondo model has an equation for canopy storage during higher rainfall intensity at each time step for the rainfall at that time. The hourly model simulations were performed for the year 1994.

Results showed that annual forest canopy evaporation ranged from 22 to 29% of gross rainfall. The annual net rainfall ranged from 71 to 78% of gross rainfall with higher values for the Rutter model and lowest for the Kondo model. The annual transpiration ranged from 727 to 733mm and may indicate the assumed potential rates. The models simulated more or less equally net rainfall, transpiration and slightly evaporation. Especially, the Deardorff predicted close to the Rutter model but the Kondo model well kept track of the storage changes at the expense of low drainage. The different evaporation rates and other fluxes resulted from different model formulations especially throughfall coefficients and drainage functions. Analysis indicated that model evaporation predictions differed much during low intensity rainfall where potential (atmospheric) evaporation demand is not satisfied. Meteorological variables such as rainfall intensity, wind speed, air pressure, temperature and solar radiation also influenced the hourly evaporation rates. Essentially, the main controls of the wet canopy evaporation were wind speed and water vapor pressure deficit. Also, the

Rutter's throughfall coefficient and drainage parameter b might had influence on the amount available to the storage for evaporation, therefore justification or calibration of these two parameters for the study area or Japan will be useful for a more equitable comparison, especially with the Modified Kondo model developed in Japan. Therefore, the models have to be validated using canopy interception observations from the forest.

The study showed that the Modified Kondo model is comparable to the famous interception models as prediction differences were small and is therefore suitable for use in hourly hydrological simulations. Moreover, the importance of the power function cannot be overemphasized as ignoring it can have significant impact on the estimation of evaporation or transpiration. The fractional cover, which is wet and dry by Deardorff (1978), seemed to have significant impact on transpiration but not much to evaporation to the Kondo model. It was shown that the water balance closed for Kondo model without including the important part of power function but did not reflect explicitly the model representative ness of physical processes. This study also makes a note that under the same conditions (e.g. evaporation and transpiration kernel, climatic and closed forest canopy cover), different forest canopy interception models may give slight different net rainfall, evaporation and transpiration values.

The canopy storage capacity decrease of 12.5% from 1.12 mm to 0.98 mm had no impact to the water fluxes for the Kondo model. The study results are in slight agreement with other studies in Japan and those shown in Table 1, for the disagreement it may be because of formulation and simulation differences (e.g. process details, data input, power function and time step).

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