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APPLICATION OF MACRO-SCALE ATMOSPHERIC AND LAND SURFACE PROCESS HYDROLOGIC MODELLING SYSTEM

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PREFACE

Climate modellers as well as hydrologists have shown great interest in the area of macroscale hydrologic land surface process modelling for use in climate models in the recent years .However, due to variability of land surface processes and parameters on time and space scales and difference in scales for atmospheric and hydrological procesess , our understanding of land surface atmosphere interactions is still very crude. No specific work has been carried out in India in this important area.

In order to initiate some work in this area at NIH the Biosphere Atmosphere Transfer Scheme - a land surface parameterization scheme developed by National Center for Atmospheric Research (NCAR) that deals with land surface atmosphere interactions ; and its modified version considering subgrid scale variability in precipitation input was studied. The study has been carried out by Dr. Divya, Sc. 'B', Atmospheric Land Surface Modelling Division and Dr. S M Seth, Sc. 'F'.

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ABSTRACT

The need of macroscale modelling of hydrological processes for the use in GCMs has attracted considerable attention of the climate modellers as well as the hydrologists in the recent years.This is mainly because the climate models consider a grid size of approx. 10^4 - 10^5 km^2 which is a macroscale for hydrological proceses. Our present understanding of land surface-atmosphere interactions and the processes and fluxes that define these interactions is limited. In India, no specific work has been carried out in this area.

In order to develop increased understanding of land surface-atmosphere interactions and to highlight the importance of macroscale hydrologic land surface modelling , this report describes the studies carried out using Biosphere Atmosphere Transfer Scheme (BATS) - a land surface parameterization scheme that considers a grid size of $4.5^{\circ} \times 7.5^{\circ}$ ($1^{\circ} \sim$ 110 km) and its modified version that allows the simulation of spatially inhomogeneous conditions in precipitation input. The model has been applied to the soil and vegetation type characteristics of Central India. An attempt has been made to study the sensitivity of energy and moisture balance components to subgrid scale variability in precipitation .The results highlight the importance of accounting for the subgrid scale heterogeinty and show the large sensitivity of energy and moisture balance components to precipitation variability in space. Future research needs in this area have been identified.

1.0 INTRODUCTION

The requirements on hydrological models for simulation of land surface processes in relation to atmospheric boundary layer have been investigated by several authors. From the hydrological researchers it was in particular Klemes (1985) who examined the suitability of hydrological models for investigating the sensitivity of water resources to climate processes. He formulated the following general requirements for these models :

(a) They must be geographically transferable and this has to be validated in the real world;

(b) Their structure must have a sound phydical foundation and each of the structural components must permit its separate validation;

(c) The accounting of evapotranspiration must stand on its own and should not be a by - product of the runoff accounting. Precipitation and potential evapotranspiration usually form the independent input variables.

It may be said that these requirements are inherent to physically based hydrological models, as they represent the system's components as they appear in nature. While physically based models are satisfactory as regards their structure , their use presents several problems ,the first relating to different scales of hydrological processes. A general overview of scale ranges of meteorological and hydrological processes is given in Fig. 1. If the fundamental differential equations of the continuum hydro- and thermo-dynamics are applied to the modelling of the hydrological land surface processes, they can only conserve a real

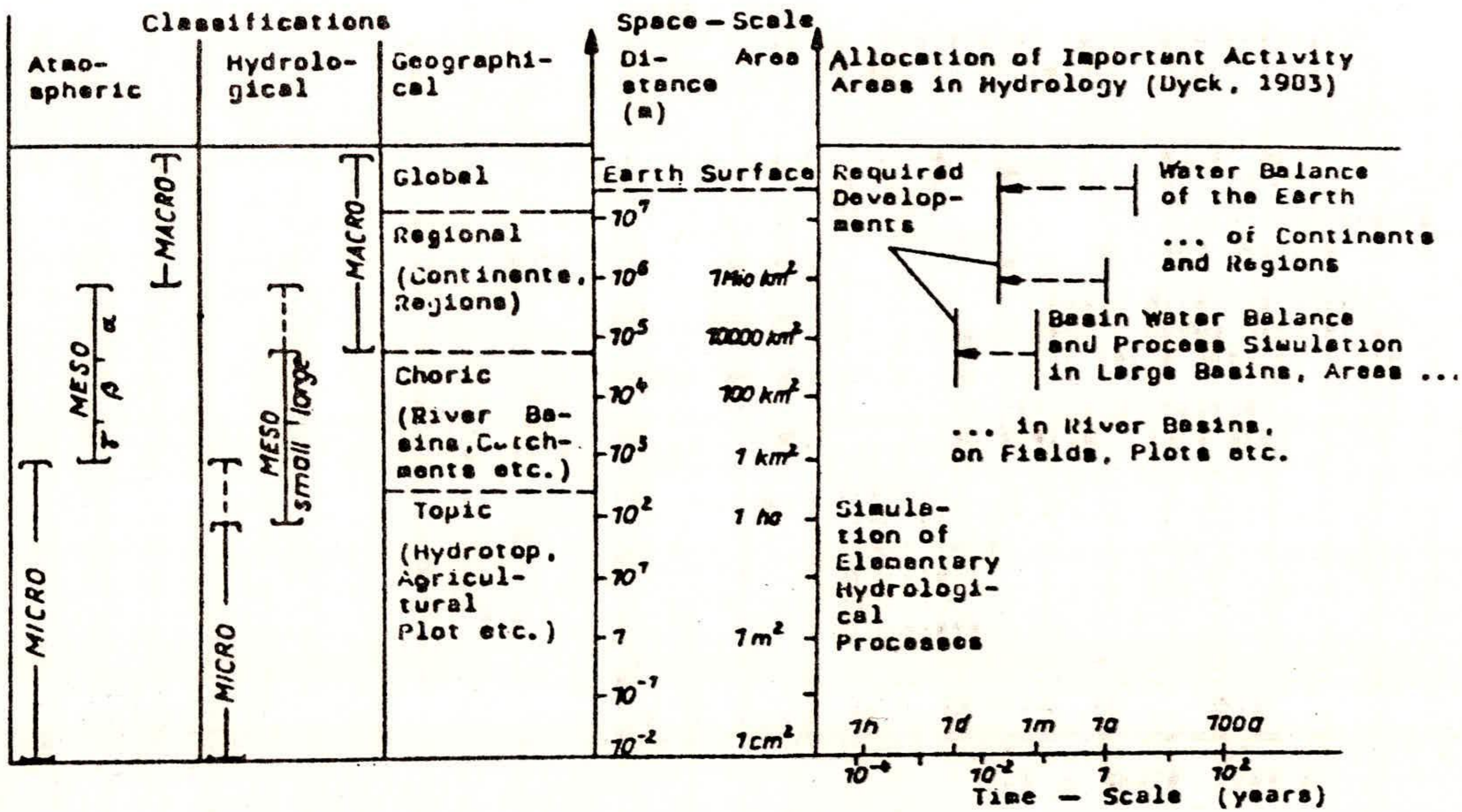

Fig. 1 : Scale Ranges of meteorological and hydrological processes

- world validity on a microscale, where the conditions of continuity , internal homogeneity etc. are sufficiently fulfilled, i.e. in a 'topic' dimension (point, elementary plot or homogeneous hydrlogical unit area of generally less than 1 km^2. Unlike land surface areas these conditions are fulfilled in the atmosphere for much larger scales.

The general circulation models, that have been currently used consider an average grid size of 5° x 5° (approx. 500 x 500 km^2) which is a macroscale for hydrological processes. These are too coarse to resolve most hydrologic and biospheric processes. Since fluxes of moisture and heat, and other hydrologic fluxes occur on a spatial scale less than that resolved by a GCM, hence these are parameterized.

2.0 REVIEW

The land surface hydrology has traditionally been incorporated into GCMs using exceedingly simple parameterizations thus grossly misrepresenting the surface fluxes. Most of the GCMs use some version of the bucket model for hydrological parameterizations. The model considers the soil as a bucket of fixed capacity of 15 cm (Fig.2). The bucket fills when precipitation exceeds evaporation and after becoming full the excess water runs off. Evaporation is computed using a wetness factor (evapotranspiration efficiency) which is a linear function of soil saturation. This is a very crude representation of land surface processes. This macroscale 'hydrology' conserves the mass(water) and net energy balance at the land atmosphere interface , but it is oversimplified in '*areal integration*' to the

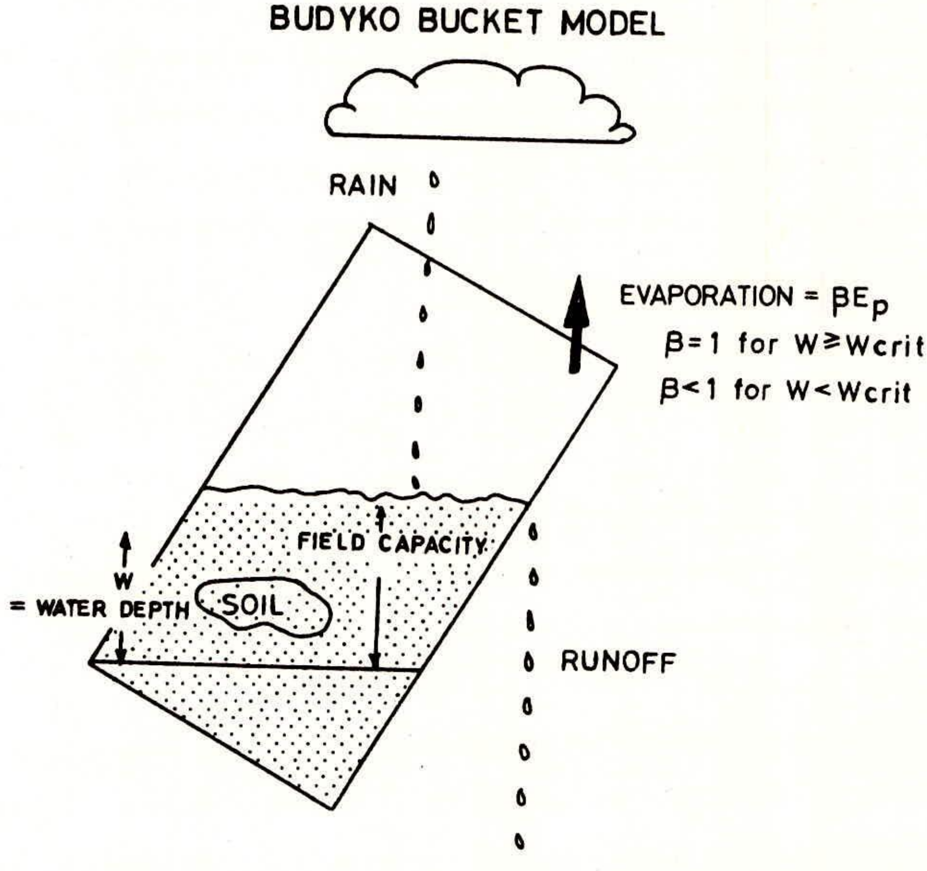

Fig. 2 : Bucket model for hydrological parameterization

extent that the results of the modelling become questionable and are in many respects not in accord with reality. Efforts were therfore directed to use physically and biologically better based models. One interesting attempt was that of Warrilow (1986) who replaced the bucket model in a GCM by an improved hydrological model. However ,this model could not be validated against observed discharges within the framework of a river basin model.

The modelling in hydrological macroscale has begun only recently. It has been examined by Nemec (1970), Dooge (1981), Eagleson (1982), Fiering (1982), and Dyck (1983). The satatement of the latter applies best to the problem of hydrology in the GCM: "One of the assumptions frequently made is that our understanding of the microscale elements and processes (in the hydrological cycle) can ,with minor modifications be extrapolated in principle to the understanding of the macroscale environment ,thus enabling reliable predictions to be made by linking the solutions to form a causal chain. Unfortunately , it seldom happens that way. Sooner or later, at some scale or characteristic dimension ,mechanistic explanation breaks down and is necessarily replaced by unverified causal hypotheses or statistical representations of the processes".

The extension of differential equations of hydro- and thermo- dynamically forced processes of moisture movement in a vertical column of the soil covered by vegetation to a basin or eventually to the large grid surface of GCMs is an excellent example of passing from a hydrological microscale to a hydrological macroscale. It is of course understandable to examine the microscale hydrological processes in order to justify the prediction that will eventually have to be made on meso or macro scale. The microscale is, however, unable to express the feedbacks , areal variabilities and other spatial integrational features needed to be included in a macroscale hydrological land surface process model.

In the recent years, several authors have developed more complex and improved land surface-biosphere models (Dickinson et al, 1986; Sellers et al, 1986). The Biosphere Atmosphere Transfer Scheme (BATS) developed by Dickinson et al (1986) is more complex than many schemes incorporated into other GCMs , although it is still highly simplified compared with reality. It incorporates most of the essential surface features including account for vegetative control on evapotranspiration, canopy effects on net radiative budget at the surface and inclusion of an improved representation of soil processes and several soil and canopy layers.

BATS, in original version does not consider the subgrid variability in precipitation, soil and vegetation parameters. It was modified at Colorado State University to include the subgrid scale variability in precipitation. In the present report, the description of BATS has been presented. The model has been applied to perform the sensitivity experiments on subgrid scale variability in precipitation considering soil and vegetation characteristics prevailing in the Central India .Future research needs and proposed studies have been emphasized.

3.0 LAND SURFACE PROCESSES IN GCM

Before discussing the Biosphere Atmosphere Transfer Scheme (BATS) it is worthwhile to have a bird's eye view on the land surface processes currently dealt in GCMs.

Land surface processes are those phenomena which control the fluxes of momentum, heat and moisture between the surface and the atmosphere over continents. Fig.3 gives the schematic representation of fluxes of momentum, energy and mass at a bare soil surface.

3.1 Surface Momentum Flux

The atmospheric boundary layer is simply the lowest layer of the atmosphere in an aerodynamic sense, under the direct influence of the underlying surface from which momentum is extracted and transferred downward to overcome surface friction. Thus, the aerodynamically rough land surface provides a sink for atmospheric momentum. The removal of this at the surface is represented by the viscous drag or horizontal shearing stress, τ, (Nm^{-2}) which by convention is a vectorial measure of the downward flux of horizontal momentum.

3.2 Surface Energy Flux

The energy flux balance at a bare soil surface may be expressed as

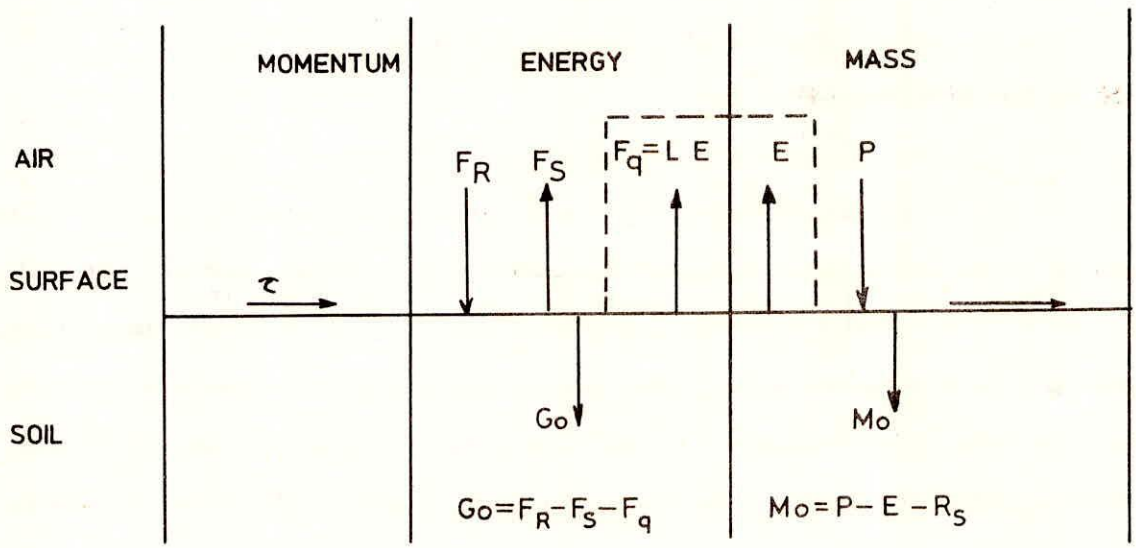

Fig. 3 : Schematic representation of the fluxes of momentum, energy and mass at a bare soil surface

$$G_o = F_R - F_s - F_q \qquad (1)$$

where all the radiative fluxes (F_R) directed towards the surface are taken to be positive and the nonradiative (G_o, F_s & F_q) fluxes directed away from the surface are positive. F_R is the net radiative flux at the surface, F_s the sensible heat flux and

$$F_q = LE \qquad (2)$$

is the latent heat flux (where L is the latent heat of evaporation, E the surface evaporation rate or turbulent flux of water vapour), G_o the flux of heat into the soil.

$$F_R = (1-\alpha)\, S^{\downarrow} + \varepsilon_o\, (F_{IR} - \sigma\, T_g^{4}) \qquad (3)$$

The fluxes given in eq.(3) are expressed in Wm^{-2}. S is the downward shortwave radiation flux, α the albedo, ε_o longwave emissivity of the surface, F_{IR} the downward longwave radiative flux , σ the Boltzman constant and T_g the ground temperature.

3.3 Surface Moisture Flux

The moisture flux at the surface can be expressed as

$$M_o = P - E - R_s \qquad (4)$$

where M_o is the net moisture flux (mass flux of water) into the soil layer, P the intensity of surface rainfall, E the surface evaporation rate and R_s the intensity of the runoff along the surface. The flux terms in eq.(4) have SI units of kg $m^{-2}s^{-1}$;

however, these rates are more commonly expressed in terms of a representative depth (of water) per unit time.

For the parameterization of G_o and M_o, a knowledge of heat conduction and water transport in the soil respectively is needed. In GCMs, this leads to the reformulation of eq.(1) as a prognostic equation for the surface temperature T_g and of eq.(3) as a prognostic equation for the mass of water stored in a specified depth of surface soil layer i.e. the soil moisture content. Their representation in BATS scheme is described in section 4.3.

The land surface's influence on the atmosphere as expressed in the above equations will vary (a) due to changes in the surface parameters α, ε_o and surface roughness length (z_o) (which affects the fluxes of heat, moisture and momentum), (b) (i)due to changes in the surface temperature and surface moisture availability, which modify F_s, F_q and F_{IR} due to atmospheric processes and to the sub surface thermal and hydrological processes or alternatively (ii) because of variations in the sub surface fluxes G_o and M_o and surface runoff R_s again due to sub-surface thermal and hydrological processes.

4.0 BIOSPHERE ATMOSPHERE TRANSFER SCHEME

The Biosphere Atmosphere Transfer Scheme (BATS), developed at National Center for Atmospheric Research, USA (Dickinson et al, 1984) is a land surface parameterization scheme for coupling with Community Climate Model (CCM). However, it can also be used as a standalone boundary package. It considers a

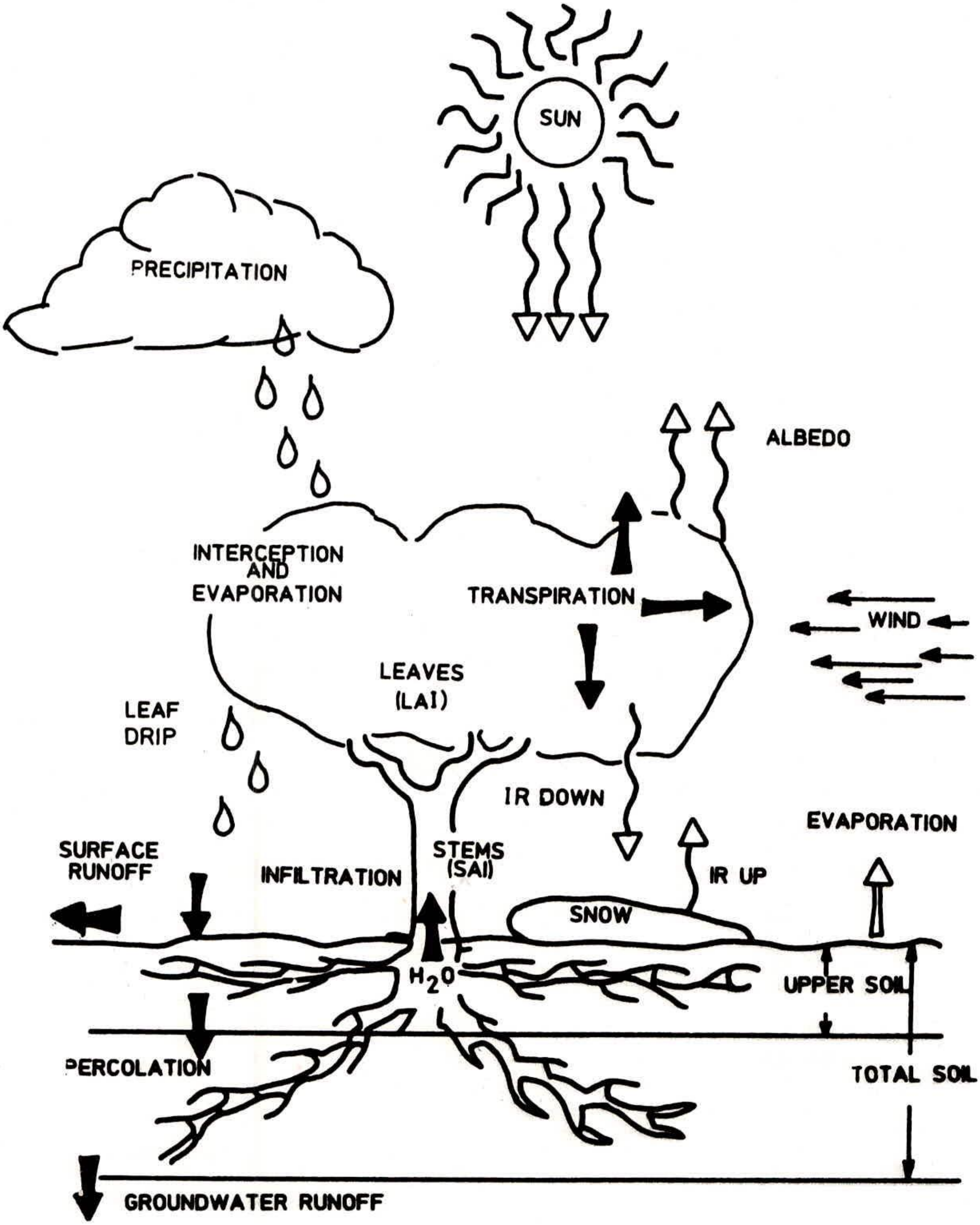

Fig. 4 : Schematic diagram illustrating the features included in the land surface parameterization scheme

grid size of 4.5° x 7.5°. Though, BATS is more complex than many other land surface parameterization schemes, it does not consider the subgrid scale availability in precipitation, soil and vegetation parameters.

4.1 Purpose

The proposes of BATS are to (i) calculate the transfers of momentum, heat and moisture between earth's surface and the atmosphere, (ii) determine the values of wind, moisture and temperature in the atmosphere, within vegetation canopies and at the level of surface observations, and (iii) determine (over land and sea ice) values of temperature and moisture (moisture content of the soil, the excess rainfall that goes into runoff etc.) quantities at the earth's surface. In order to carry out these calculations it is necessary to prescribe a predominant land surface category for each surface grid point. BATS can represent a very wide range of vegetation - soil coupled systems by selection of the appropriate land cover and soil description class. It includes a complete range of vegetation types, in addition to soil parameterizations.

4.2 Features

Fig. 4 shows the schematic diagram illustrating the features included in the BATS. It is to be pointed out here that the plant almost covers one grid element (4.5° x 7.5° approx.). It incorporates most of the essential surface features including a vegetation canopy, surface and rooting zone soil layers, variable albedo and hydrological characteristics. The treatment of the canopy energy and moisture balance includes (i) interception of precipitation by vegetation and subsequent evaporative loss and leaf drip, (ii) moisture uptake by plant roots, distributed between the upper and full soil column, and (iii) stomatal resistance to transpiration.

Precipitation incident on the surface is in part intercepted by the vegetation foliage, some of the intercepted precipitation is reevaporated and some drops off the ground along with the non intercepted precipitation. Part of the water incident on the ground infiltrates into the soil and the rest travels along the surface or near surface to enter streams. The water in the soil passes downward and may travel below the active surface layer tapped by roots into groundwater reservoirs which also eventually supply streamflow. At the same time plants extract water from the soil through their roots and move it to the atmosphere by transpiration through their leaves. The stomatal resistance to transpiration is also taken into account. The soil column is divided into three nested layers, an upper, layer a root zone layer and a total layer. Only upper two layers are thermally active.

4.3 Land Surface Parameterization in BATS

4.3.1 Soil Temperature

As mentioned earlier, the fluxes of heat into the soil are parameterized in terms of soil temperature. BATS follows Deardorff's (1978) 'force restore' method for formulating tendency equations for temperature in two thermally active soil layers.

These equations take into account the following processes - direct shortwave and longwave absorption by ground, sensible and latent heat fluxes, conductive loss to subsurface and conductive gain from upper layer based on linear damping. The soil and subsoil temperature are obtained from

$$\frac{\partial T_{g1}}{\partial t} = \frac{c_1 h_s}{\rho_s c_s d_1} - \frac{c_2 (T_{g1} - T_{g2})}{\tau_1} \tag{5}$$

$$\frac{\partial T_{g2}}{\partial t} = - c_3 \left[\frac{(T_{g2} - T_{g1})}{\tau_1} + c_4 (T_{g2} - T_{g3}) + Q_{sf} \right] \tag{6}$$

where

T_{g1} = Surface soil and/or snow temperature (also referred to as T_g)

T_{g2} = Subsurface soil and/or snow temperature

T_{g3} = Fixed annual mean deep soil temperature

t = Time

c_1 = $2\pi^{1/2} = 3.5449$

h_s = $(S_g + (F_{IR}^{\downarrow} - F_{IR}^{\uparrow}) - F_s - L_{v,s} F_q - L_f S_m - L_f W_{m1})$ (7)

c_2 = $2\pi = 6.28$

c_3 = Rate of subsoil relaxation; = 0.2 (assumed). This factor depends on how deep a soil thermal reservoir is considered (which is somewhat arbitrary). Its choice was dictated by the requirement that T_{g2} have a seasonal cycle but not a significant diurnal one and correspond to a thermal reservoir of 1 to 2 m soil.

c_4 = Damping of soil surface temperature to annual mean value. The parameter c_4 is set to zero everywhere except over permafrost where T_{g3} is set to freezing T_m.

τ_1 = Period of heating = 8.64×10^4 second (= 1 day)

where

S_g = Solar flux absorbed over bare ground at earth's surface.

$F_{IR}^{\downarrow} - F_{IR}^{\uparrow}$ = Net IR (long wave) flux from atmosphere to bare ground

F_s = Atmospheric sensible heat flux from ground to atmosphere

F_q = Atmospheric moisture flux from ground to atmosphere

$L_{v,s}$ = Latent heat of evaporation or sublimation

L_f = Latent heat of fusion

Q_{sf} = $L_f W_{m2} c_1 / (\rho_s c_s d_1 c_2)$ = Rate of subsoil temperature change because of melting or freezing

S_m = Rate of snow melt

W_{m1} = Rate of melting (negative for freezing) of surface soil water

W_{m2} = Rate of melting (negative for freezing) of subsurface soil water

$\rho_s c_s$ = Specific heat of subsurface layer per unit mass

d_1 = $(k_s \tau_1)^{1/2}$ = Soil depth influenced by a periodic heating (about 0.2 m for a typical soil)

where

k_s = soil or snow thermal conductivity ($m^2 s^{-1}$)

Eqs. (5), (6) and (7) use diurnal cycle of soil heating. These are solved using finite difference technique and the implementation of these equations depends upon different surface type viz. bare soil, snow covered land, bare sea ice or snow covered sea ice.

4.3.2 Soil Moisture

In direct analogy to the study of need of heat conduction in the soil to provide a sound physical basis for evaluating the 'surface temperature', there is also a need to understand more about the dynamics which govern the movement of water in the soil in order to model changes in the profile of soil moisture content. It is to be emphasized here that there is a strong interactive coupling between the thermal and hydrological properties and processes in the soil. In a model with both interactive surface hydrology and interactive land surface temperature, the value of soil moisture content has an important bearing on the evaluation of T_g and vice-versa.

4.3.2.1 Precipitation

The surface rainfall rate, P, is regarded as an externally determined component of the surface moisture balance. This, at the ground is obtained as the sum of net precipitation from each layer in the atmosphere, in global circulation models. In BATS, it is assumed to fall as snow P_s, if for the lowest model layer, $T_1 \leq T_c$ or as rain P_r if $T_1 > T_c$, where T_1 is the temperature of lowest model layer and $T_c = T_m + 2.2$; T_m is the melting or freezing point of water.

$$P_s = P,\ P_r = 0, \qquad \text{if } T_1 \leq T_c$$

$$P_s = 0,\ P_r = P, \qquad \text{if } T_1 > T_c \qquad (8)$$

4.3.2.2 Soil moisture budget

Moisture incident on the ground either infiltrates the soil or is lost to surface runoff. In BATS, soil moisture is represented by two parameters:

S_{tw} = total water in the rooting zone depth (D_o)

S_{twmax} = maximum total soil water

S_{sw} = surface soil water representing water in the upper layer of soil (D_1)

S_{swmax} = maximum upper soil water

D_o and D_1 are functions of land cover type and are given in Table 2.

S_{sw} and S_{cw} in absence of vegetation are given as

$$\frac{\partial S_{sw}}{\partial t} = G - R_s + Y_w \qquad (9)$$

$$\frac{\partial S_{tw}}{\partial t} = G - R_s + R_g \qquad (10)$$

where $G = P_r + S_m - F_q$ (11)

is the net water applied to the surface, P_r the rainfall, S_m the snowmelt and F_q the evaporation, R_s the surface runoff, Y_w the transfer of water to the upper layer from the rest of the column and R_g the leakage down to subsoil and ground water reservoirs (representing the bulk of the runoff). The terms F_q, R_s, R_g and Y_w are parameterized on the basis of multilayer soil model (Dickinson, 1984).

4.3.2.3 Infiltration and percolation to ground water

For a single soil type for each grid square, the following properties (that are mostly dependent upon the soil texture), are specified (Table 3)

i. Porosity P_{ORSL} ie. at saturation $1m^3$ of soil holds P_{ORSL} (m^3) of water

ii. Soil water suction (negative potential)

$$\emptyset = \emptyset_o \, s^{-B}$$

where the values of $\emptyset_o$ and B are listed in Table 3 and

s = volume of water divided by volume of water at saturation and = ρ_{sw}/P_{ORSL}.

iii. Hydraulic conductivity $K_w = K_{wo} \; s^{2B+3}$ with values for $K_{wo}(ms^{-1})$ given in Table 3, which represents the flow rate for saturated soil due to gravity.

Water represented by s diffuses through the soil with a diffusivity

$$D = - K_w \, \partial\emptyset/\partial s = K_{wo} \, B \, s^{B+2} \qquad (12)$$

Besides the diffusive movement, there is gravitational drainage which dominates the flow for large enough length scales. Thus the subsoil drainage expression becomes

$$R_g = K_{wo} \; s^{2B+3} \qquad (13)$$

4.3.2.4 Evaporation

It is difficult to parameterize the evaporative terms F_q and the transfer between the upper soil layer and below. In BATS the expressions are based on the behaviour of soil column that is initially at field capacity and dried by a diurnally varying potential evaporation applied at the surface. The following parameterization for F_q is adopted in BATS

$$F_q = \text{minimum of } (F_{qp}, F_{qm}) \qquad (14)$$

where F_{qp} is the potential evaporation and F_{qm} the maximum moisture flux through the wet surface that the soil can sustain.

F_{qp} depends upon meteorological variables viz. surface air density, wind speed and vapour pressure deficit.

Since potential evaporation rarely exceeds 4×10^{-7} ms^{-1}, soil much wetter than field capacity will evaporate at the potential rate generally.

During process of evaporation because of daytime heating, soil moisture distribution approaches a self similar profile. For such a profile the water loss from the top layer is proportional to the water loss from the total active layer.

4.3.2.5 Surface runoff

The parameterization of surface runoff, R_s, is guided by the criteria that there should be small surface runoff at the soil moisture of field capacity and complete surface runoff at saturated soil.

4.3.2.6 Snow cover

In BATS only the snow surface processes are modeled explicitly. The water on snow surface is put directly into the soil, whereas real melt or rain water has to percolate through the snow pack and may refreeze. BATS implicitly neglects melting at the bottom of the snow pack due to heat conducted from the ground (ground melt) unless this heat reaches the top snow surface.

4.3.3 Drag Coefficients

In the BATS C_D is calculated as a function of C_{DN}, the drag coefficient for neutral stability, and Ri_B is the surface bulk Richardson number, i.e.,

$$C_D = f(C_{DN}, Ri_B), \qquad (15)$$

where C_{DN} is the drag coefficient for neutral stability, Ri_B is the surface bulk Richardson number .

In reality, the C_D value for heat is somewhat larger under unstable conditions and somewhat smaller under stable conditions. The neutral drag coefficient is obtained from mixed-layer theory.

(a) Vegetation

Over vegetated grid squares, the neutral drag coefficient is estimated by a linear combination for drag coefficients or for vegetation over bare soil or over snow. It is assumed that the snow coefficient has the same value as that of the ocean. The form of area averaging that has been assumed would be more appropriate for spatially separated vegetated and nonvegetated regions within the grid square. By contrast, a sparsely but uniformly vegetated area can exert considerably more drag than a more heavily vegetated area.

(b) Leads over sea ice

Over sea ice, it is important to allow for leads. This is done by prescribing a fraction of surface a covered by leads, over which the assumed water temperature = 18°C, and at sea level the saturated mixing ratio of leads = 3.3×10^{-3} kg kg^{-1}. Drag coefficients are calculated separately for the sea ice and for lead surfaces and then are linearly combined according to the relative fraction of the lead.

4.3.4 Energy Fluxes With Vegetation

At each land grid point a fractional vegetation cover σ_f is prescribed, which varies seasonally as a function of subsoil temperature T_{g2}.

4.3.4.1 Parameterization of foliage variables

The one-sided surface area of vegetation per unit area of ground consists of transpiring surfaces specified by a leaf area index, i.e. (L_{AI}) and nontranspiring surfaces (including dead vegetation) specified by a stem area index (S_{AI}). The S_{AI} is a constant for each land type, whereas the L_{AI} has a seasonal variation, using the same dependence on subsoil temperature as used for vegetation cover.

4.3.4.2 Vegetation storage of intercepted precipitation and dew

When it rains, the surfaces of vegetation become covered with a film of water before drip through and stem flow carry water to the ground. This water can then reevaporate to the air, but at the same time transpiration is suppressed over wet green leaves. Similarly, the formation of night time dew can keep foliage cool in the morning and suppress transpiration. Typical values for reevaporation of intercepted rainfall are in the range of 10 to 50% of rainfall, depending primarily on rainfall intensity. The suppression of transpiration by wet leaves is also significant. Snowfall is also intercepted by foliage, and frost formation on foliage commonly occurs. These are of somewhat less significance for the water budget because of lower evapotranspiration rates at low temperatures. Hence, it is reasonable to assume that vegetation storage of solid water is the same as liquid water. In doing so, the larger initial water storage of snow interception and its frequently more rapid removal by blow off is ignored. A maximum water storage of 0.0002 m x L_{SAI} is assumed. The water stored by canopy per unit land surface area is calculated from the incident precipitation and difference between transpiration and water flux to the plant surface ,

4.3.4.3 Fluxes from foliage

The water flux from wet foliage follows similar considerations but, in addition, the resistance to water flux by stomata needs consideration.

4.3.4.4 Stomatal resistance

The term stomatal resistance, refers to the total mechanical resistance encountered by diffusion from inside a leaf to outside. This term is sometimes referred to as leaf resistance to distinguish it from the resistance due to the stomata alone. Water vapour inside leaves is maintained at or very near its saturated value, for otherwise the mesophyllic cells of the leaf would desiccate and the leaf wilt. The stomata are pores which, when open, are the main conduits for transpired water. Hence, the net resistance r_s to water passing from the inside to the outside of the leaf depends largely on the size, distribution, and degree of opening of these stomata. However, some water diffusion also occurs through leaf cuticles, which can be the primary route for transpiration when the stomata are closed. In general, the opening of the stomata, and hence r_s, change with various environmental parameters, including inability of roots to supply adequately the transpiration demand.

4.3.4.5 Root resistance

The plant water uptake in each soil layer s limited by the difference between soil and the leaf potential divided by an effective resistance. This effective resistance depends on the total length of root per unit area and the internal plant resistance per unit root length. When the soil is dry enough, the diffusion of water from the soil to the roots also contributes to this resistance.

4.3.4.6 Soil moisture and snow cover with vegetation

Finally, it is noted that, in the presence of vegetation the soil moisture and snow cover

$$\frac{\partial S_{sw}}{\partial t} = P_r(1 - \sigma_f) - R_s + Y_w - \beta E_{tr} - F_q + S_m + D_w \qquad (16)$$

$$\frac{\partial S_{tw}}{\partial t} = P_r(1 - \sigma_f) - R_w - E_{tr} - F_q + S_m + D_w \qquad (17)$$

$$\frac{\partial S_{cv}}{\partial t} = P_s(1 - \sigma_f) - F_q - S_m + D_s \qquad (18)$$

where S_{cv} is the snow cover measured in terms of liquid water equivalent ,P_s the snow precipitation rate, F_q the rate of sublimation ,β = fraction of transpiration from the top soil layer, D_w is the rate of excess water dripping from leaves per unit land area, D_s is the corresponding rate at which excess snow falls from the leaves, and R_w=R_s+R_g is the total runoff.

4.4 Land Type Assignment

Based on the two global land surface archives-vegetation and cultivation data of Matthews (1983, 1984) and the land use and soils data of Wilson (1985) BATS uses 18 dominant land types (Table 1). These 18 classes of land cover are used to define a

Table 1 : Vegetation/land cover assignment in BATS

1. Crop/mixed farming
2. Short grass
3. Evergreen needleleaf tree
4. Deciduous needleleaf tree
5. Deciduous broadleaf tree
6. Evergreen broadleaf tree
7. Tall grass
8. Desert
9. Tundra
10. Irrigated crop
11. Semi-desert
12. Ice cap/glacier
13. Bog or marsh
14. Inland water
15. Ocean
16. Evergreen shrub
17. Deciduous shrub
18. Mixed woodland

wide variety of land surface, hydrological and vegetation properties.

The vegetation/land cover parameters for the 18 land cover types are given in Table 2, which are based on literature review and intelligent guessing by Dickinson et.al. (1986).

4.5 Soil Type Assignment

In BATS, twelve texture classes have been specified. Soil class 1 corresponds to coarse (equivalent to sand) and 12 to very fine (equivalent to heavy clay).Texture class 6 is comparable to loam soil. Eight colour classes have been assigned in BATS with the scale stretched at the light end. Table 3 gives the soil parameters for different soil types.

4.6 Flow and Block Diagrams

Figs. 5 and 6 show the flow and block diagrams of the boundary package BATS. Subroutine BNDRY calls individual physical process subroutines and evaluates parameters common to several routines. In particular it provides the relative soil moisture from the model moisture and maximum soil moisture storage. It calls subroutine DRAG to obtain transfer coefficients between the lowest model layer and the surface (canopy plus ground).

The vegetation part of code is only executed for grid squares with vegetation cover greater than 0.01. The coefficient of transfer of heat and momentum from leaves is calculated. Foliage water is modified by intercepted rainfall. The

Table 2 : Vegetation/Land cover parameters

Parameter	Land Cover/Vegetation Type																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
a) Maximum fractional vegetation cover	0.85	0.80	0.80	0.80	0.80	0.90	0.80	0.0	0.60	0.80	0.10	0.0	0.80	0.0	0.0	0.80	0.80	0.50
b) Difference between maximum fractional vegetation cover and cover at temperature of 269 K	0.6	0.1	0.1	0.3	0.3	0.5	0.3	0.0	0.2	0.6	0.1	0.0	0.4	0.0	0.0	0.2	0.3	0.2
c) Roughness length (m)	0.06	0.02	1.0	1.0	0.8	2.0	0.1	0.05	0.04	0.06	0.1	0.01	0.03	0.0024	0.0024	0.1	0.1	0.8
d) Depth of the total soil layer (m)**	1.0	1.0	1.5	1.5	2.0	1.5	1.0	1.0	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0
e) Depth of the upper soil layer (m)**	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
f) Rooting ratio (upper to total soil layers)	3	8	10	10	10	12	8	9	4	3	8	5	5	5	5	5	5	10
g) Vegetation albedo for wavelengths <0.7μm	0.10	0.10	0.05	0.05	0.08	0.04	0.08	0.20	0.09	0.08	0.17	0.80	0.05	0.07	0.07	0.05	0.08	0.06
h) Vegetation albedo for wavelengths >0.7μm	0.30	0.30	0.23	0.23	0.28	0.20	0.30	0.40	0.26	0.28	0.34	0.60	0.18	0.20	0.20	0.23	0.28	0.24
i) Minimum stomatal resistance ($s\ m^{-1}$)	150	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250
j) Maximum LAI	6	2	6	6	6	6	6	0	6	6	6	0	6	0	0	6	6	6
k) Minimum LAI	0.5	0.5	5.0	1.0	1.0	5.0	0.5	0.0	0.5	0.5	0.5	0.0	0.5	0.0	0.0	5.0	1.0	3.0
l) Stem (& dead matter) area index	0.5	4.0	2.0	2.0	2.0	2.0	2.0	0.5	0.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
m) inverse square root of leaf dimension ($m^{-1/2}$)	10	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
n) Light sensitivity factor ($m^2\ W^{-1}$)	0.01	0.01	0.03	0.03	0.03	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03

Table 3 : Soil type assignment in BATS

I/FUNCTIONS OF TEXTURE

Parameter	Texture Class (from sand (1) to clay (12))											
	1	2	3	4	5	6	7	8	9	10	11	12
a) Porosity (volume of voids to volume of soil)	0.33	0.36	0.39	0.42	0.45	0.48	0.51	0.54	0.57	0.60	0.63	0.66
b) Maximum soil suction (m)	0.03	0.03	0.03	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
c) Saturated hydraulic conductivity (mm s^{-1})	0.2	0.08	0.032	0.013	8.9×10^{-3}	6.3×10^{-3}	4.5×10^{-3}	3.2×10^{-3}	2.2×10^{-3}	1.6×10^{-3}	1.1×10^{-3}	0.8×10^{-3}
d) Ratio of saturated thermal conductivity to that of loam	1.7	1.5	1.3	1.2	1.1	1.0	0.95	0.90	0.85	0.80	0.75	0.70
e) Exponent "B" defined in Clapp & Hornberger (1978)	3.5	4.0	4.5	5.0	5.5	6.0	6.8	7.6	8.4	9.2	10.0	10.8
f) Fraction of water content at which permanent wilting occurs	0.095	0.128	0.161	0.266	0.300	0.332	0.378	0.419	0.455	0.487	0.516	0.542

II/FUNCTIONS OF COLOR

Parameter	Color (from light (1) to dark (8))							
	1	2	3	4	5	6	7	8
a) Dry soil albedo								
< 0.7 µm	0.23	0.22	0.20	0.18	0.16	0.14	0.12	0.10
≥ 0.7 µm	0.46	0.44	0.40	0.36	0.32	0.28	0.24	0.20
b) Saturated soil albedo								
< 0.7 µm	0.12	0.11	0.10	0.09	0.08	0.07	0.06	0.05
≥ 0.7 µm	0.24	0.22	0.20	0.18	0.16	0.14	0.12	0.10

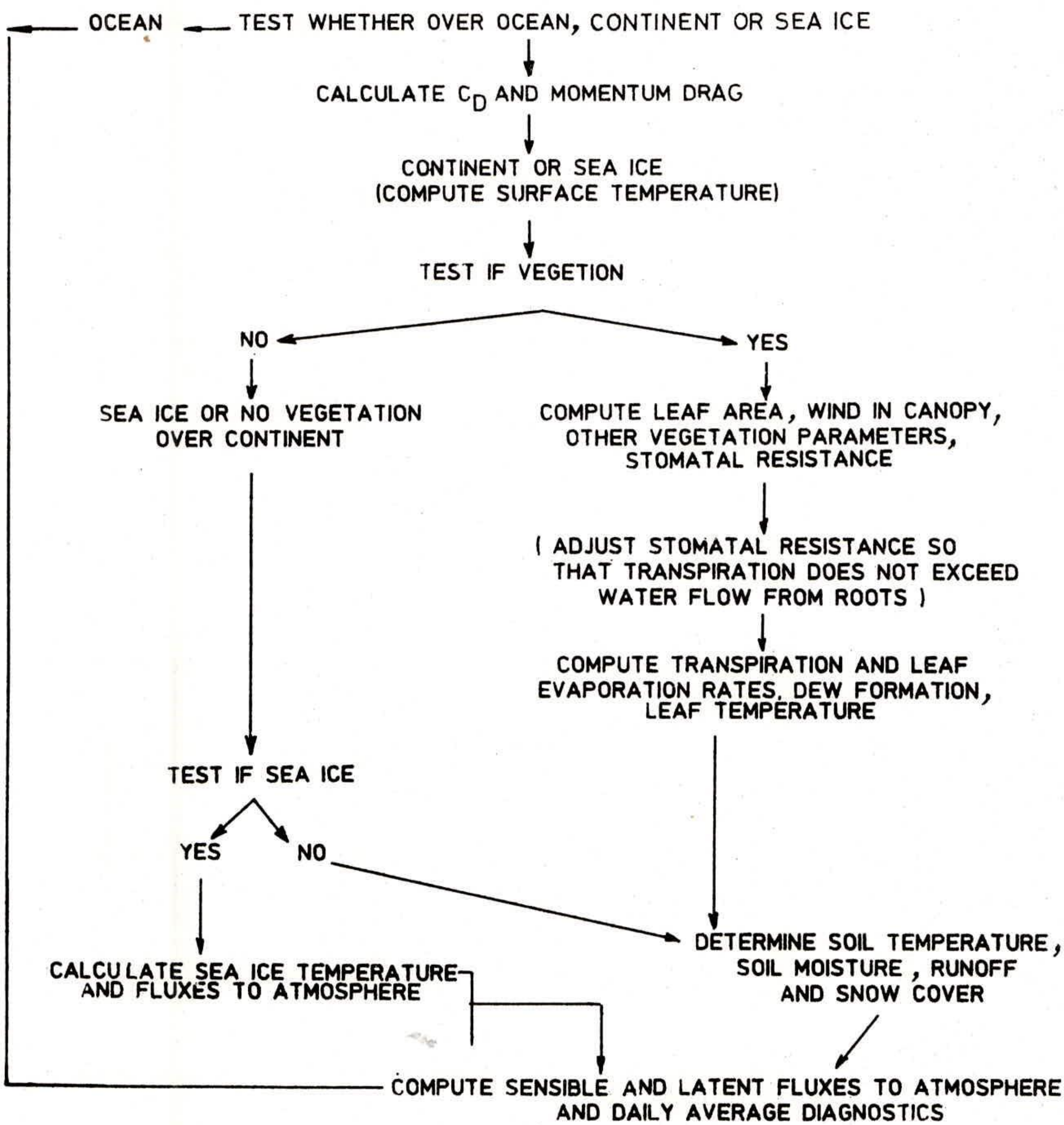

Fig. 5 : Flow diagram showing major features in BATS

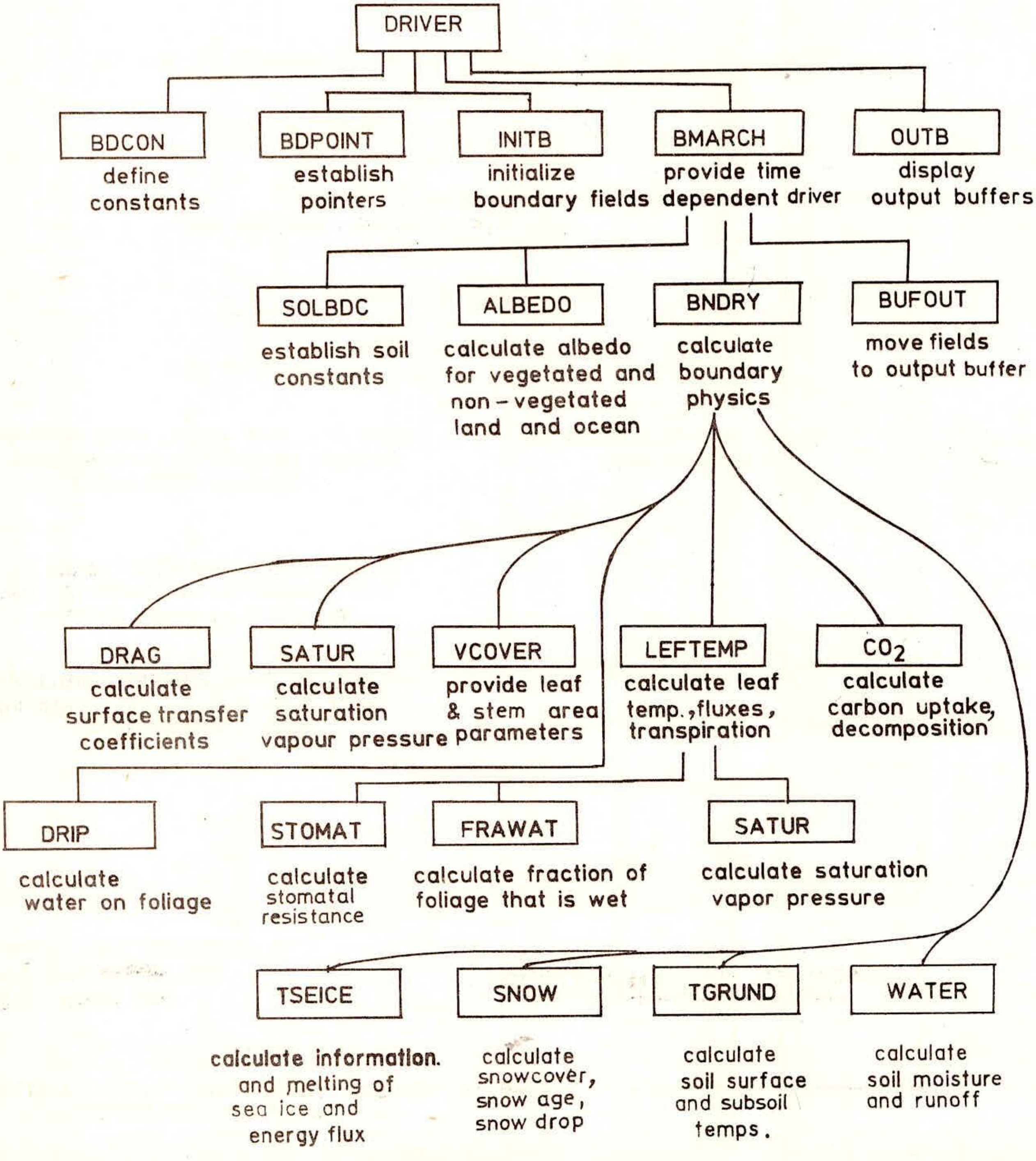

Fig. 6 : Block diagram showing major features in BATS

temperature of the foliage (leaves) is calculated. Any rain or snow intercepted by leaves in excess of their maximum capacity is determined as falling to the ground and saved for soil water or snow budget calculations.

Returning to a calculation for all surfaces, rain or snow incident on the ground (minus any that was intercepted by the foliage) and partition soil evaporation into that from soil water and that from overlying snow are calculated. Routines are called to calculate the sea ice or the ground temperature and the budgets of snow cover and soil water. The updated temperatures, soil moisture, and foliage transpiration are used to determine net fluxes of heat and momentum from the surface to the lowest atmospheric model layer.

5.0 SUBGRID SCALE VARIABILITY IN PRECIPITATION

5.1 Application of BATS to Soil and Vegetation Characteristics of Central India

Though, BATS has incorporated many land surface physical processes, it is still crude as it does not take into account the subgrid scale variability in precipitation, soil and vegetation parameters. In reality the grid size of $4.5^{\circ} \times 7.5^{\circ}$ will have spatially inhomogeneous precipitation intensities and soil and vegetation characteristics . BATS considers the homogeneous precipitation intensity throughout the grid. Thus, a single value of precipitation intensity is specified for the whole grid (average precipitation intensity) . Although ,the average of precipitation intensities (inhomogeneous) within the grid may be same as the average precipitation intensity on the grid, the fluxes of energy and moisture evaluated in the two cases would be different. The surface fluxes may thus be grossly misrepresented. BATS was modified at Colorado State University to allow the simulation of spatially inhomogeneous conditions in precipitation input. The precipitation intensity, the interarrival time between precipitation pulses and the storm duration generated in the model are assumed to follow exponential distribution. The computation are performed considering the soil and vegetation characteristics in Central India. The input data are given in Table 4.

5.2 Sensitivity Experiments

In order to study the effect of subgrid scale variability in precipitation fields on various components (fields) of energy and moisture budget, the grid was divided into 16 square subgrids, so that each subgrid forms 1/16 th part of the grid. The fluxes of energy and moisture were evaluated for the following two cases . All other parameters except precipitation were kept the same for each subgrid, in the model.

Case I: With subgrid

The precipitation generated in the model is spatially inhomogeneous. In a given time step any one subgrid out of sixteen subgrids gets wet and the choice of the subgrid to get wet is random , while the other 15 subgrids receive zero precipitation input in that timestep. The average of fields of energy and moisture budget of different subgrids (average of spatially inhomogeneous distributed fields) were evaluated, considering

Table 4 : Input Parameters in BATS

Surface Type Parameters	Central India in summer (April)
1. Vegetation type	5
2. Fractional veg. cover	.80
3. Snow cover (mm of water)	0
4. Snow age (Nondim.)	0
5. Relative humidity	0.7
6. Rootzone soil water (mm)	500
7. Upper soil water (mm)	30
8. Total soil water (mm)	2500
9. Carbon uptake (kg C/m s)	0
10. Respiratory rate (kg C/m s) (accum. carbon uptake of soil + veg.)	1.0
11. Anemometer temperature (/K)	300
12. Soil texture class	10
13. Soil colour class	7

Central India (Deciduous Broadleaf)
precipitation variability

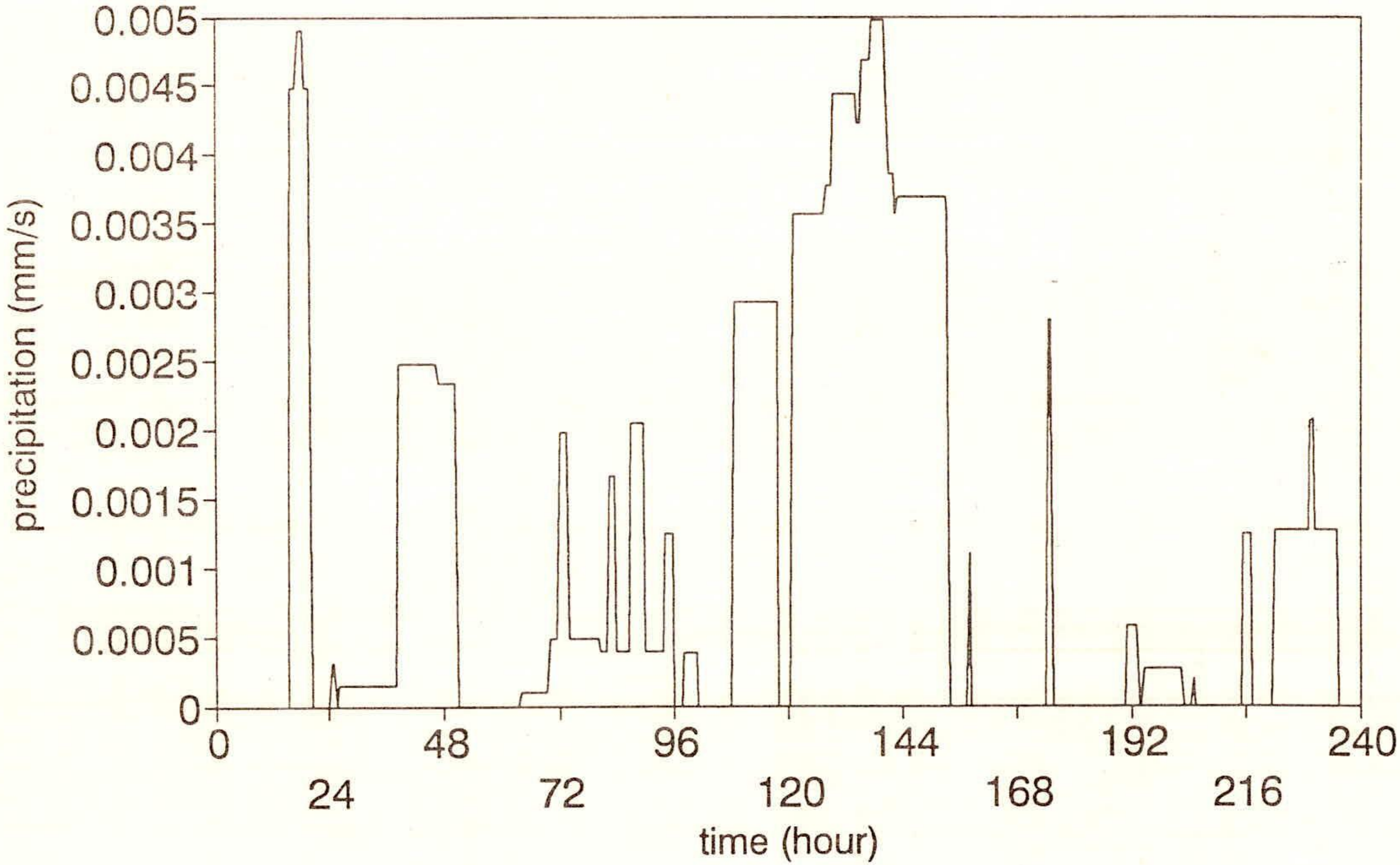

Fig. 7 : Average precipitation on the grid

spatially inhomogeneous precipitation input.

Case II: Without subgrid

The average volume of precipitation computed from case I is applied uniformly on the whole grid i.e. it is equivalent to all 16 subgrids receiving same amount of precipitation in a time step. At a given time step, the average precipitation intensity for the whole grid is same as the average of precipitation intensities on each subgrid computed in previous case. The intensity of precipitation (which in the previous case was on one subgrid) is in this case reduced by 16 times and the fields are evaluated for the whole grid as a single unit (as in BATS). Figure 7 shows the average precipitation on the whole grid.

Figure 8 shows the variation of upper soil moisture with time considering the two cases with (Case I) and without (Case II) subgrid. The upper soil moisture for Case II is higher than when precipitation with higher intensity is concentrated on a subgrid (Case-I). The depth of precipitation in case-II is lower than the depth of precipitation in Case-I where it is considered over only one subgrid.

In Case-II, the depth is less and a major part of precipitation infiltrates to satisfy the moisture demand of the soil. As a result the surface runoff in Case-II is lower than case I (Fig.9). Since the soil considered in the two cases is clay loam having a hydraulic conductivity of about 3.2×10^{-3} mm s^{-1}, the flow rate for saturated soil due to gravity is low and the total runoff is the surface runoff in both the cases (Fig.10).

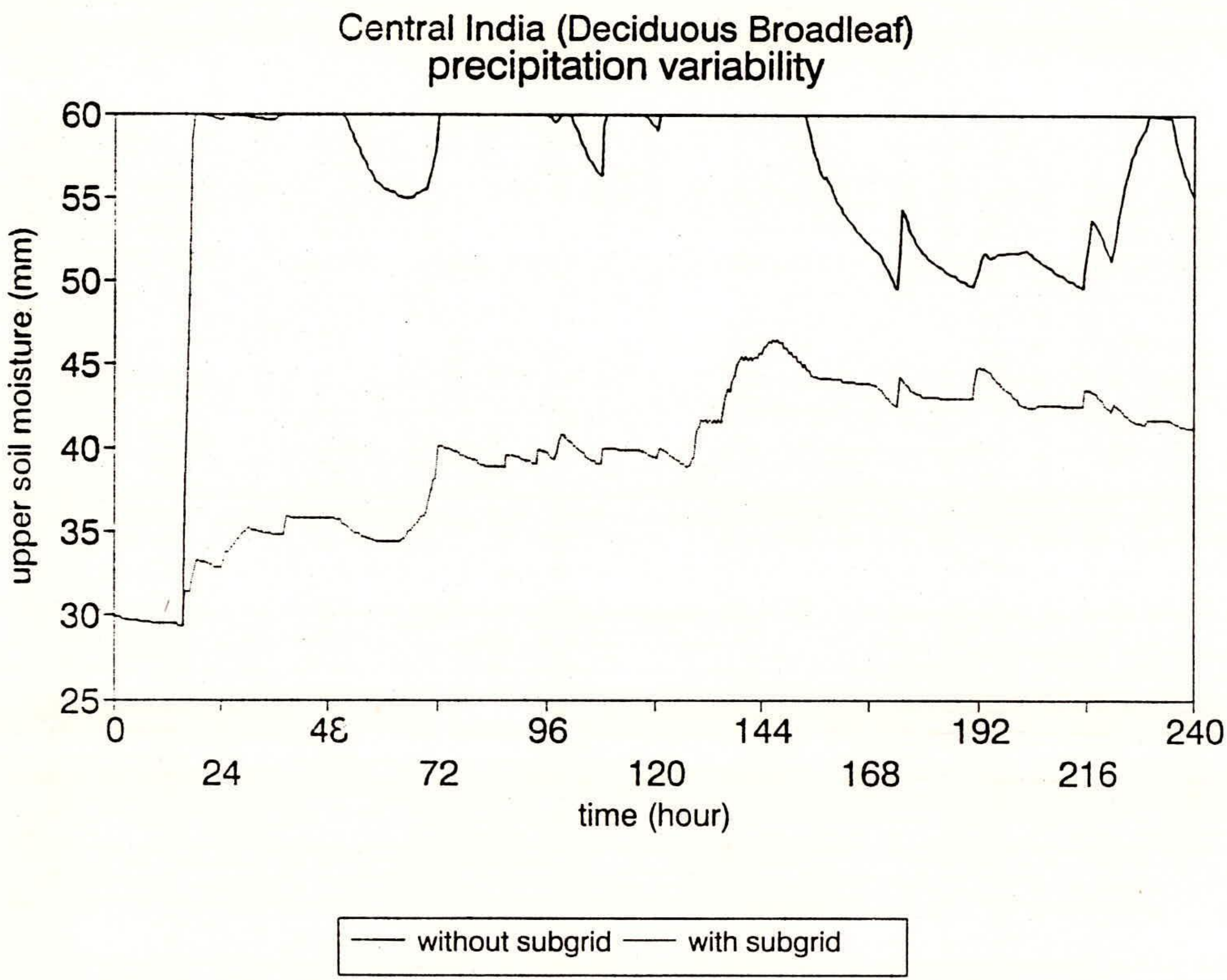

Fig. 8 : Temporal variation of upper soil moisture with and without sub-grid

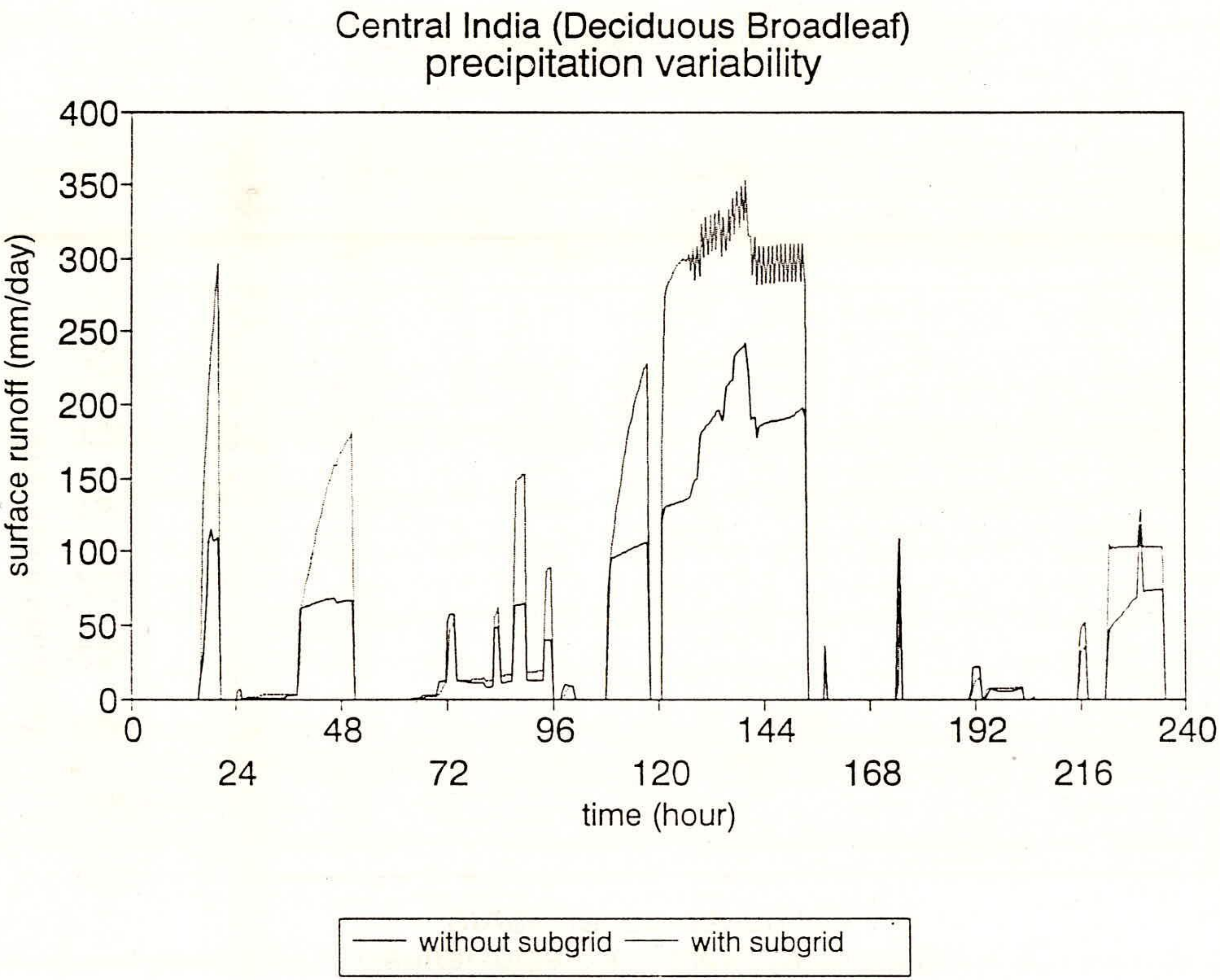

Fig. 9 : Temporal variation of surface runoff with and without subgrid

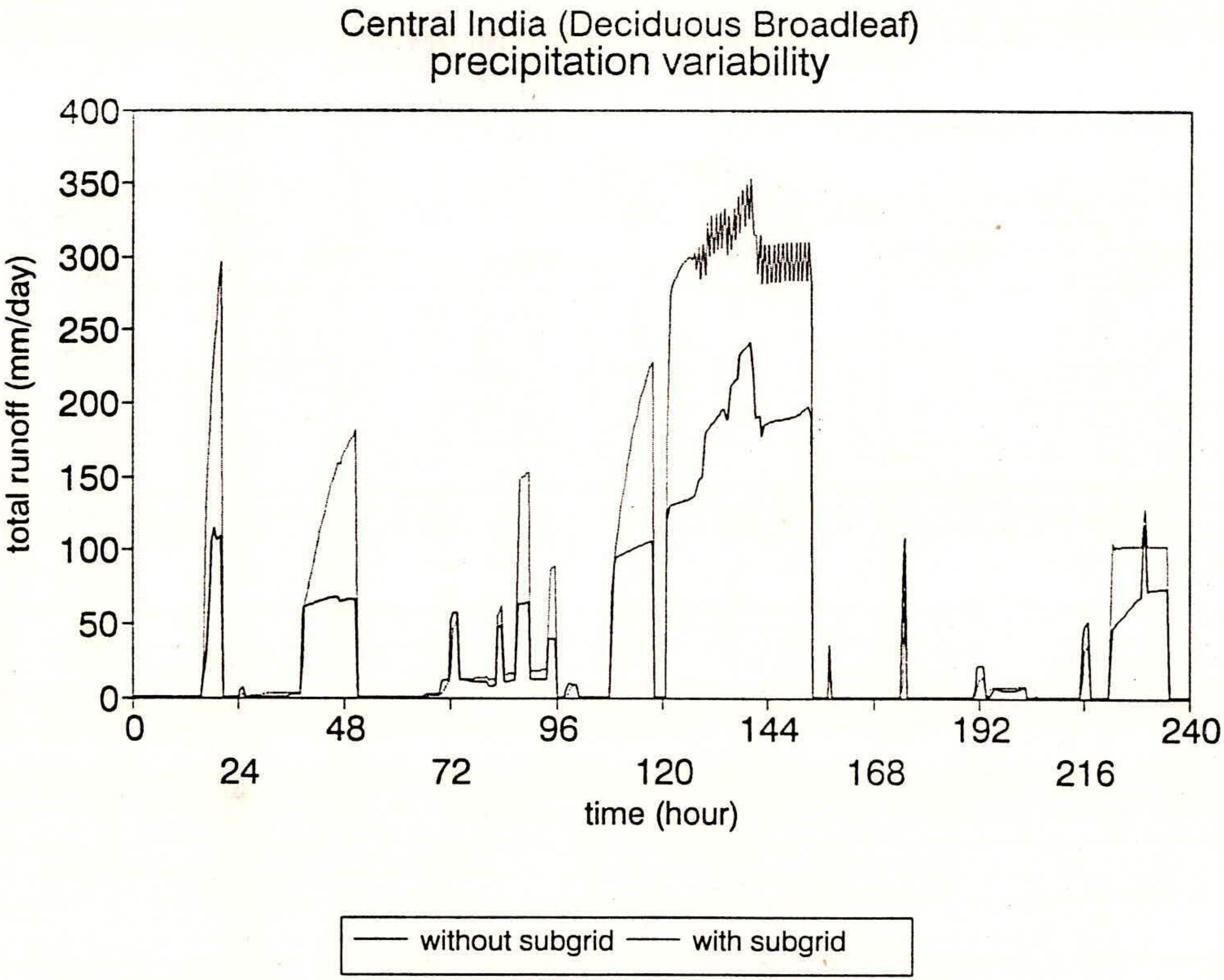

Fig. 10 : Temporal variation of total runoff with and without sub-grid

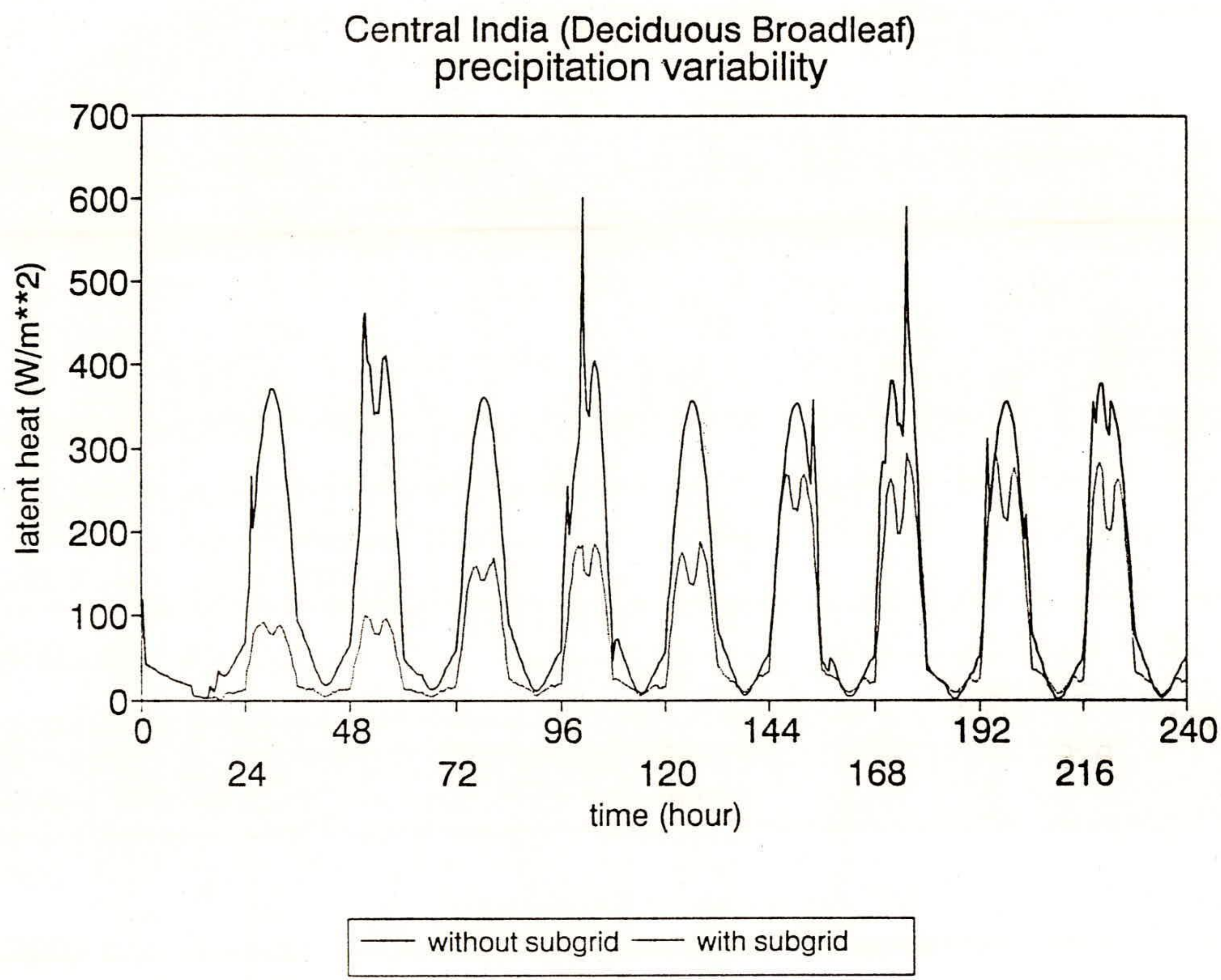

Fig. 11 : Temporal variation of evaporative flux with and without sub-grid

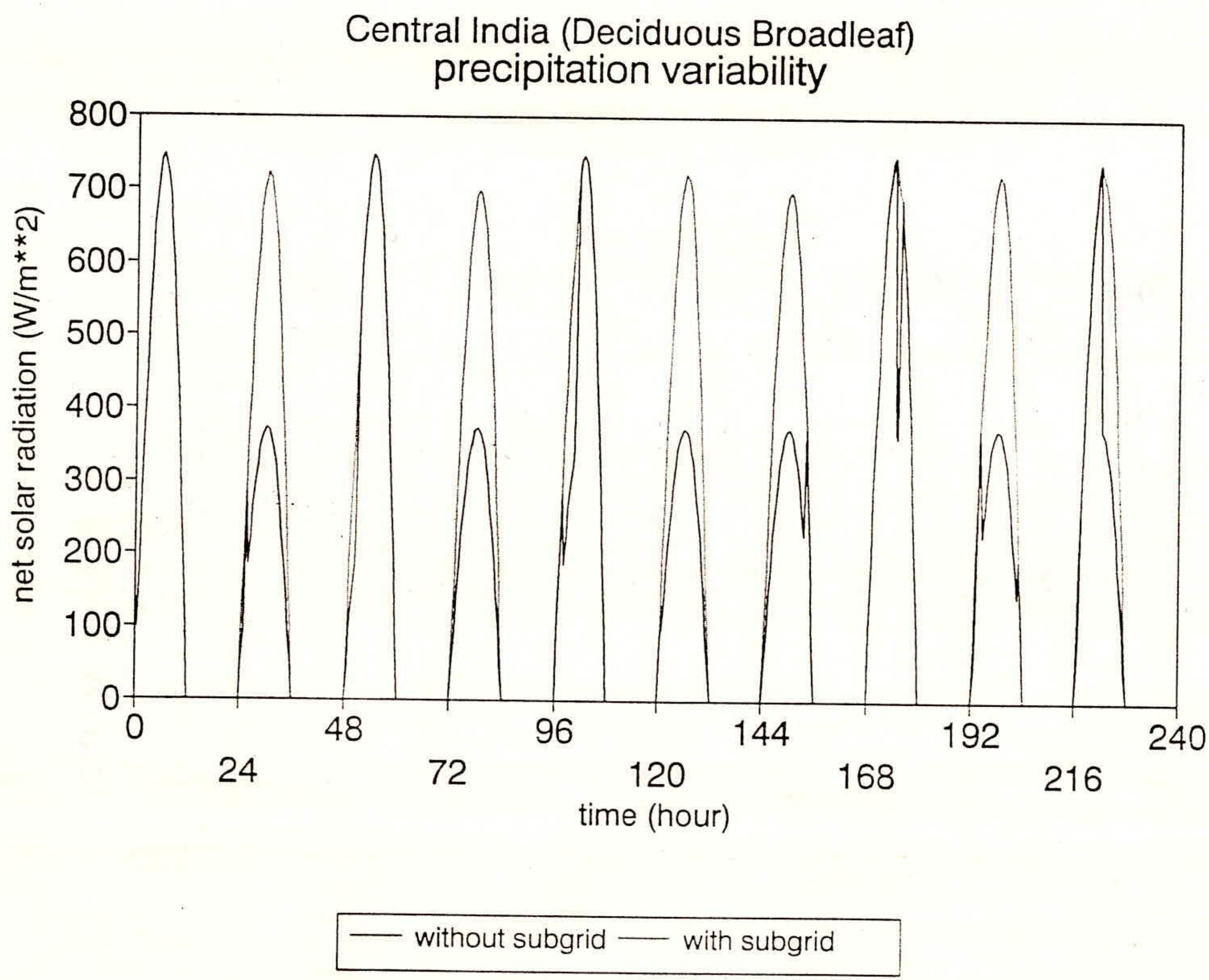

Fig. 12 : Temporal variation of net solar radiation with and without subgrid

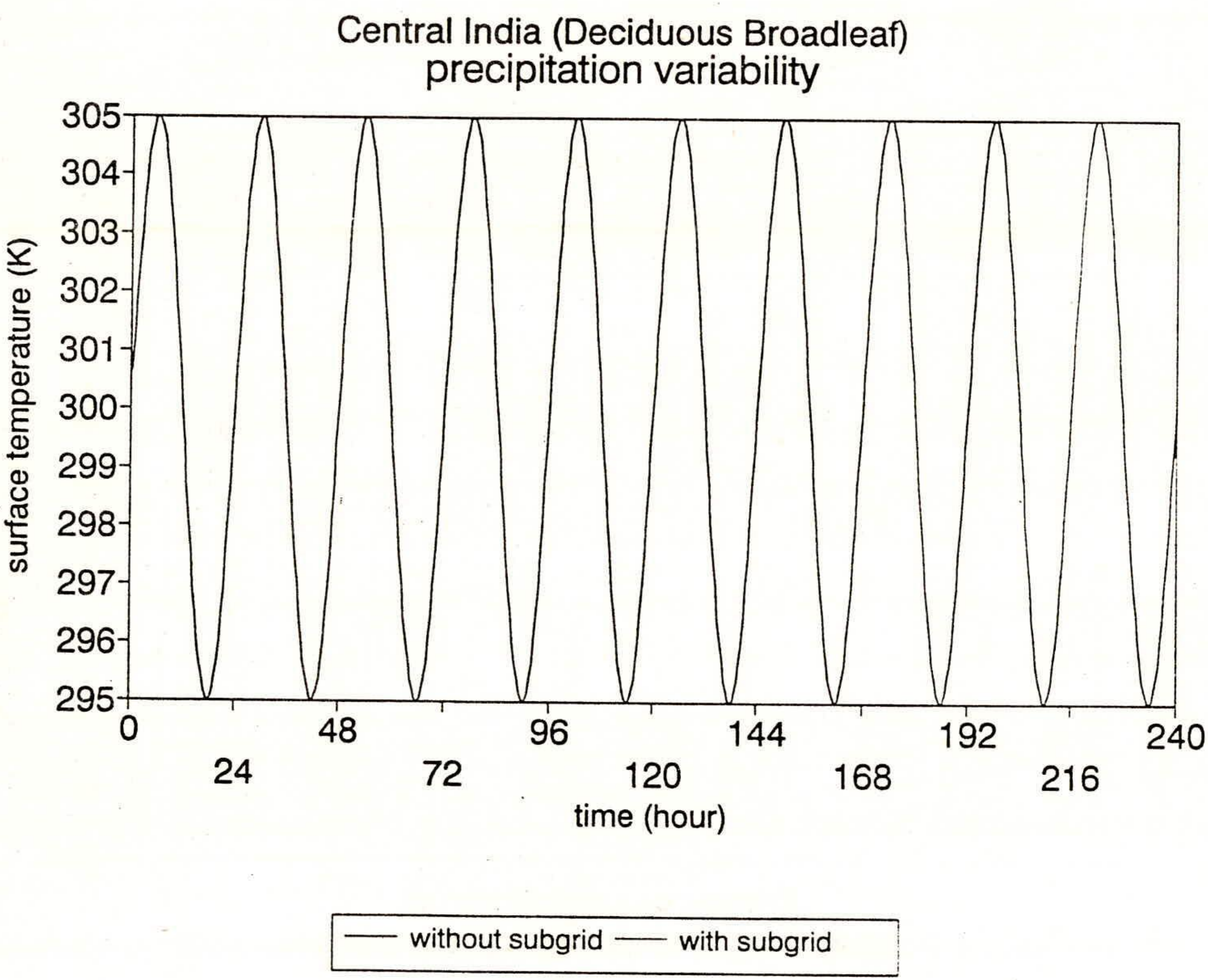

Fig. 13 : Temporal variation of surface temperature with and without sub-grid

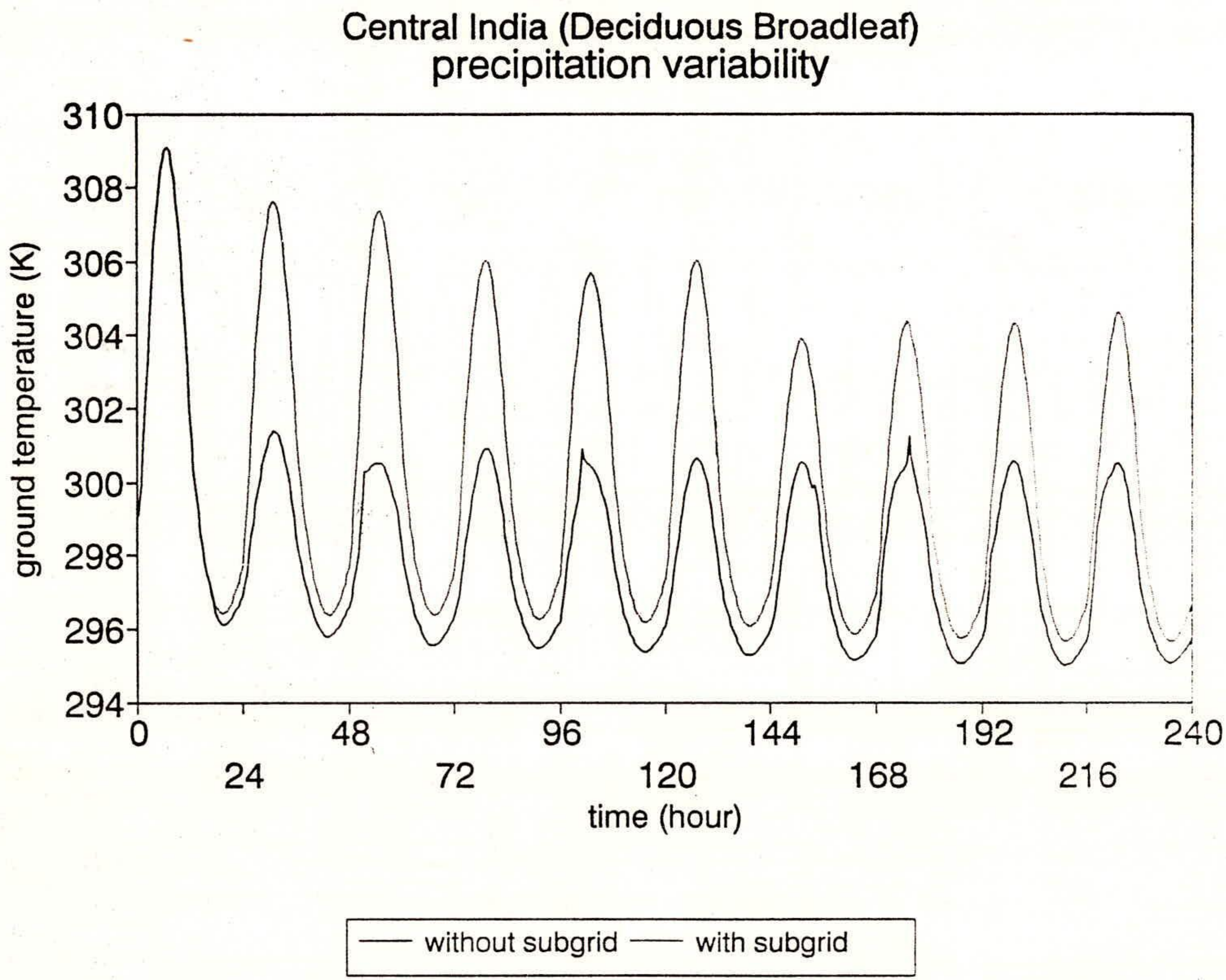

Fig. 14 : Temporal variation of ground temperature with and without sub-grid

Due to more moisture availability in the upper soil zone in Case-II as compared to Case-I, the evaporative loss is higher in the former case (Fig.11).

The model cuts down the solar radiation during precipitation. For Case-II the precipitation is on the whole grid in contrast to case I, where the precipitation is on a subgrid only and hence more net solar radiation at the surface in the latter case (Fig.12).

The model considers the same value of surface temperature in both the cases (Fig.13). However, in Case-II less solar energy is available to heat the ground, hence the ground temperature here is less than for case-I (Fig.14).

6.0 REMARKS AND FUTURE SCOPE

The results clearly indicate that the energy and water balance components are sensitive to subgrid scale variability in precipitation. The sensitivity experiments were performed here for 10 days simulation. In order to perform long term experiment, the zenith angle (depends on latitude, solar declination for a time of the year) dependence of solar radiation is to be included. In reality, there is a great subgrid scale variability in soil and vegetation parameters also, which needs to be incorporated into land surface parameterization schemes. For developing increased understanding of atmosphere - land surface interactions and in order to assess the potential effects on global and regional hydrology, there is a need to perform sensitivity analysis with fully coupled land surface - global atmosphere models or regional models as RAMS with subgrid scale variability in precipitation, soil and vegetation.

No model exists which can meet requirements of GCM and is river basin oriented. The validation of the modeling system can be made using the two level technique proposed by Nemec (1988) for macroscale hydrologic land surface modelling.

The first level model must be able to supply the required inputs for climate models on one hand and river basin models on the other (independently of the space scale applied in the modelling approach). It considers a GCM grid size and is principally related to moisture exchange with the atmosphere and runoff production.

The second level model is concerned with the flow processes; surface flow, inter flow and ground water flow. Sub dividing GCM grid into subgrids, the size depending upon areal variability of hydrological and climatic conditions, the heat and moisture fluxes are to be estimated for each subgrid, considering all meteorological parameters (as air temperature, humidity etc.) as lumped inputs or as uniformly distributed within each subgrid. Subareas of significantly different hydrological regime, in particular for evapotranspiration and runoff formation may be determined and treated separately within each subgrid unit. The outputs from first level model are taken to second level models, that are related to river basin and also to GCMs. The second level models developed for selected test river basins are to be used for comparison of simulated with observed river discharges.

The output of second level models permits the validation of modelling system.

6.1 Proposed Studies

Using the modified version of BATS studies have already been initiated, taking the data information for Central India, on sensitivity of energy and water balance components to subgrid scale variability in precipitation. The results will be reported elsewhere.

The effect of subgrid scale heterogeneity in soil and vegetation parameters on energy and water balance components will be studied taking Indian soil, vegetation types and climatological parameters. The studies will also be carried out including solar zenith angle dependence of solar radiation for long term simulation. Application of two level modeling approach for macro scale hydrologic land surface modeling will also be attempted for validation of this modeling approach, using the available hydrological data.

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