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BIOSPHERE ATMOSPHERE TRANSFER SCHEME

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NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAVAN
ROORKEE (UP) - 247 667
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PREFACE

Land surface - atmosphere interactions play an important role in determining realistic climatic change scenarios using climate models. However, due to variability of land surface processes and parameters on time and space scales, 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 develop capabilities 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 (modified at Colorado State University, USA) considering subgrid scale variability in precipitation input has been studied. This user's manual focuses upon the description of the model (BATS) in detail including various physical processes that define the land surface atmosphere interactions.

The report has been prepared by Sh R Mehrotra and Dr Divya, Scientist 'C', Atmospheric Land Surface Modelling Division.

(S M SETH)
DIRECTOR

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ABSTRACT

The land surface parameterization scheme - Biosphere, Atmosphere Transfer Scheme (BATS) developed at National Centre for Atmospheric Research has been studied to understand the physical processes involved in land surface atmosphere interactions. Attempts have been made to describe all the processes taken into account in BATS in a more simplified way. Wherever needed, processes are explained with the help of sketches. This user's manual provides in detail the features and structure of the model; the computer requirement to run the model; the program description - main drive program and subroutines used; input data description and output description.

The model calculates the transfers of momentum, heat and moisture between earth's surface and the atmosphere; determines the values of wind, moisture and temperature in the atmosphere, within vegetation canopies and at the level of surface observations and; determines (over land sea ice) values of temperature and moisture (moisture content of the soil, the excess rainfall that goes into runoff etc.) quantities at the earth surface. This land surface parameterization scheme accounts for vegetative and soil control on evapotranspiration and runoff efficiencies and for effects of seasonally varying canopy cover. The modification of BATS at Colorado State University to allow for variability in precipitation within the subgrid has also been focused upon.

1.0 INTRODUCTION

1.1 Land Surface Processes in GCM

Land surface processes are those phenomena which control the fluxes of momentum, heat and moisture between the surface and the atmosphere over continents.

The general circulation models, that have been currently used consider an average grid size of 4° x 5° (approx. 400 x 500 km^2) due to limitations in computer memory and time and a desire to perform long term experiments. Fluxes of moisture and heat and other hydrologic fluxes occur on a spatial scale less than that resolved by a GCM. The land surface hydrology has traditionally been incorporated into GCMs using exceedingly simple parameterizations thus grossly misrepresenting the surface fluxes.

Early GCMs used some version of the bucket model for hydrological parameterizations. The model considers the soil as a bucket of fixed capacity of 15 cm (Fig.1). 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. Most GCMs in current use are equipped with one - dimensional empirical runoff ratio and evapotranspiration efficiency functions (Carson, 1982). GCM grid size being larger than typical storm or basin areas, important subgrid scale variabilities at the ground lead to misrepresentation of the fluxes by the simple one dimensional formulas.

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 developed by Dickinson et al. accounts for vegetative control on evapotranspiration, canopy effects on net radiative budget at the surface and includes an improved representation of soil processes and contains several soil and canopy layers.

BATS was modified at Colorado State University to include the subgrid scale variability in precipitation. In the present report the model description of BATS, land surface processes in BATS, input and output requirement have been presented.

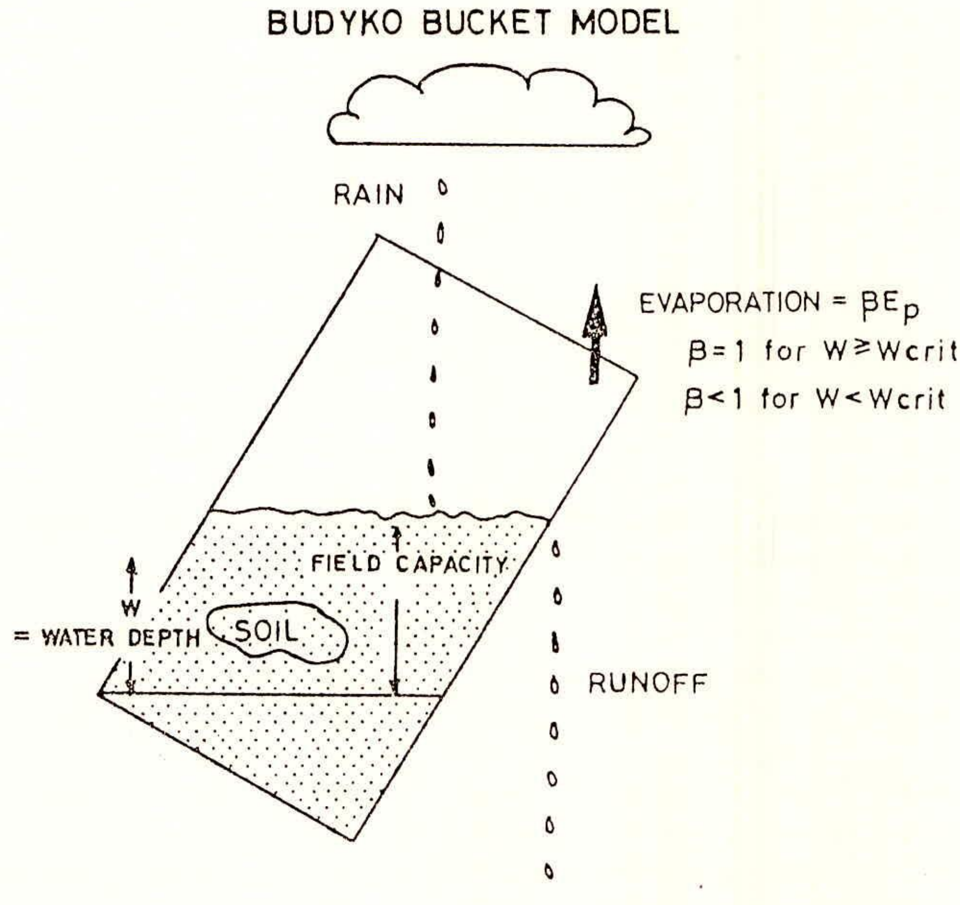

Fig. 1 Bucket model for hydrological parameterization

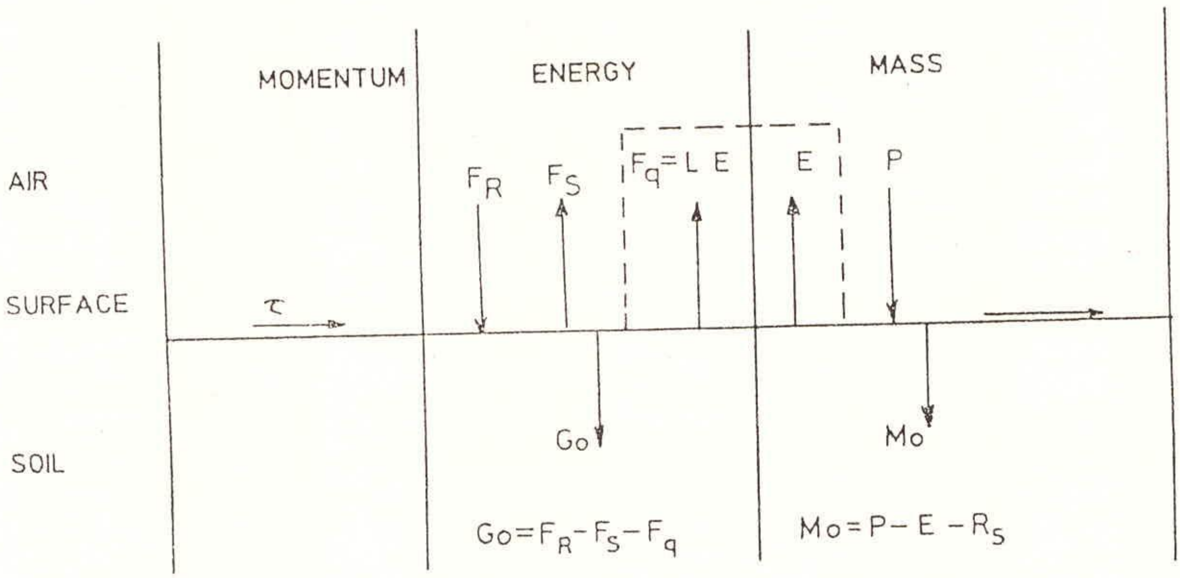

Fig. 2 Schematic representation of the fluxes of momentum, energy and mass at a bare soil surface

1.2 Fluxes at the Land Surface

Fig. 2 gives the schematic representation of fluxes of momentum, energy and mass at a bare soil surface.

1.2.1 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.

1.2.2 SURFACE ENERGY FLUX

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

$$G_o = F_R - F_s - F_q \tag{1}$$

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

$$F_q = LE \tag{2}$$

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.

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

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.

1.2.3 SURFACE MOISTURE FLUX

The moisture flux at the surface can be expressed as

$$M_o = P - E - R_s \tag{4}$$

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.

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 3.0.

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.

2.0 BIOSPHERE ATMOSPHERE TRANSFER SCHEME (BATS)

2.1 General

The Biosphere Atmosphere Transfer Scheme (BATS), developed at National Center for Atmospheric Research, USA (Dickinson et al,

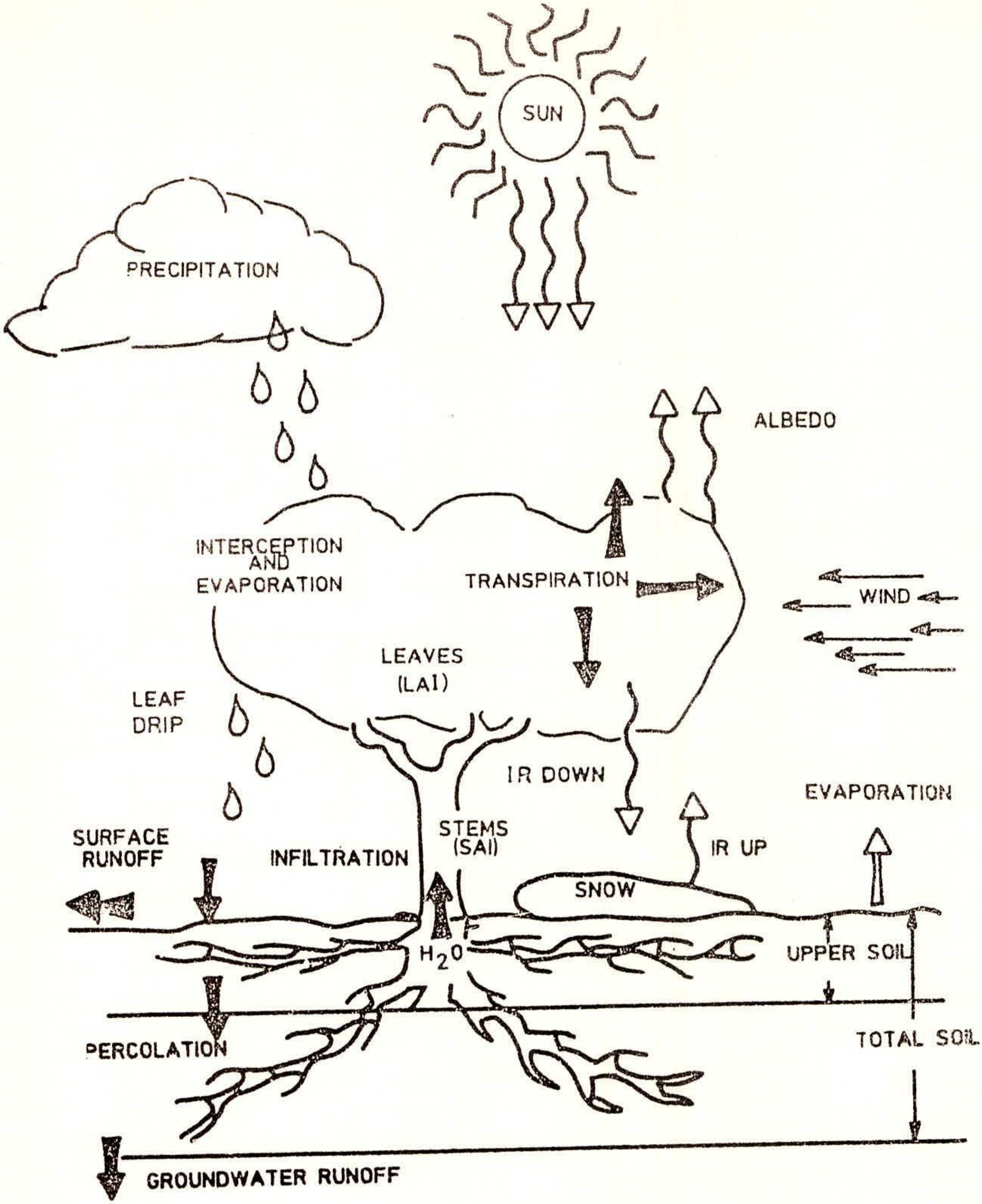

Fig. 3 Schematic diagram illustrating the features included in the land surface parameterization scheme

1986) is a land surface parameterization scheme for coupling with Community Climate Model (CCM). However, it can also be used as a stand alone boundary package. Though, BATS is more complex than many other land surface parameterization schemes, it does not consider the variability in precipitation, soil and vegetation parameters within the grid. The model has been modified at Colorado State University, USA to allow for the variability in precipitation within the grid.

The purposes 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.

2.2 Features

Fig. 3 shows the schematic diagram illustrating the features included in the BATS. 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 include (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 re-evaporated 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 or 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.

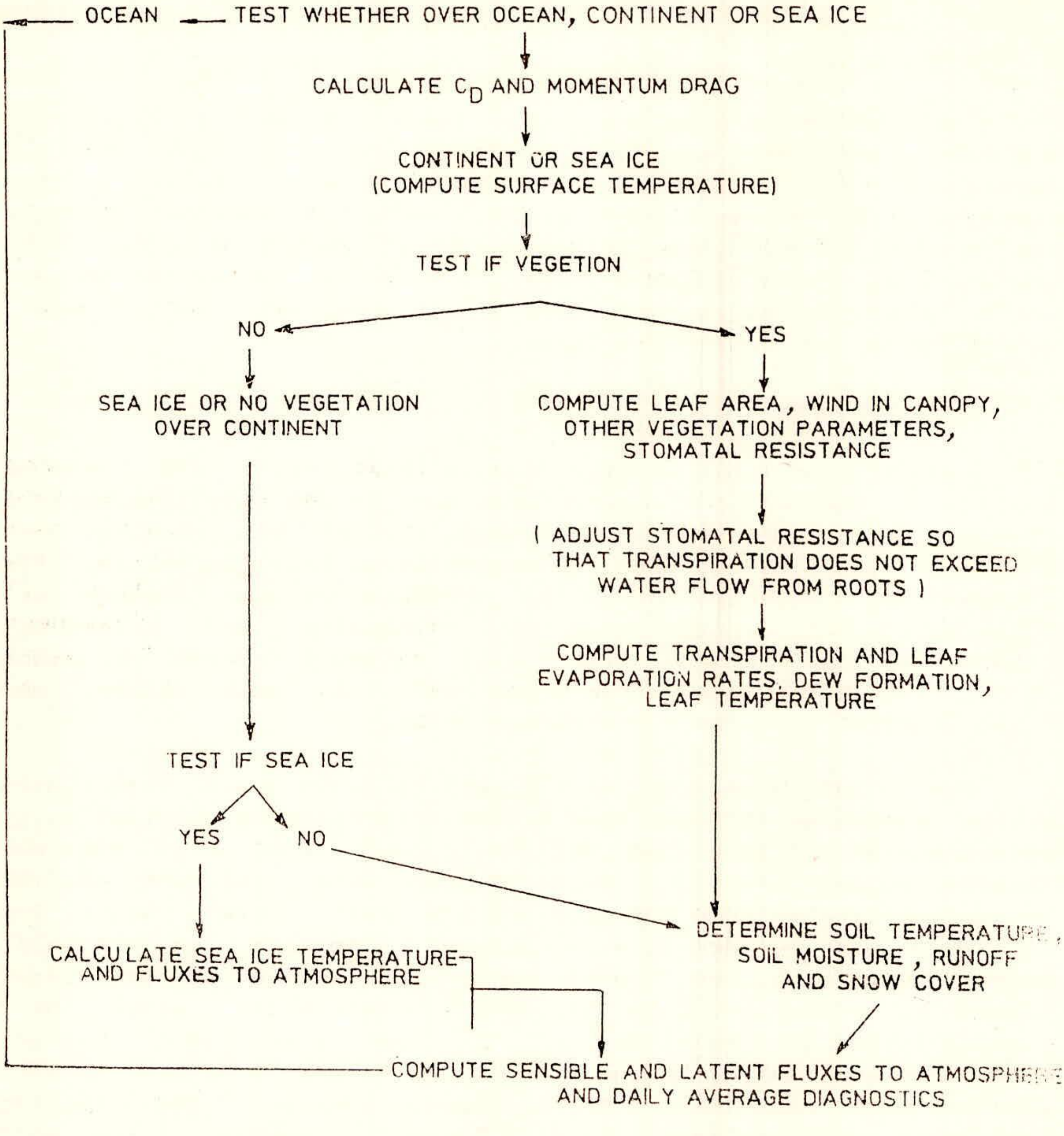

Fig. 4   Flow diagram showing major features in BATS

```
BDCON
BDPOINT
INITB           RAING_J
BMARCH ====>    SOLBDC
OUTB            ALBEDO
                ZENITH
                BNDRY  ====> DRAG   ====> DRAGDN ====> DEPTH
                BUFOUT       SATUR
                             VCOVER

                             DRIP
                             LEFTEM ==================> STOMAT
                             CO2    ====> CARBON        FRAWAT
                                          TSEICE        ROOT
                                          TGRUND        SATUR
                                          SNOW          LFDRAG
                                          WATER         CONDCH
                                                        CONDCQ
                                                        DERIV
```

Fig. 5 Flow from the DRIVER and order of subroutines in the model

2.3 Structure

Fig. 4 shows the flow diagram of the boundary package BATS. Fig. 5 gives the flow from the driver and order of subroutines. 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 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.

2.4 Computer Requirement

The model can be run on any large computer, viz., VAX, DEC, VAXSTATION, DECSTATION. However, in order to run it on a PC for point calculations, slight modifications need to be made in the program with regards to the dimension.

3.0 LAND SURFACE PARAMETERIZATION IN BATS

3.1 Soil and Vegetation Types

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.

Table 1 : Vegetation/land cover assignment in BATS

1.	Crop/mixed farming
2.	Short grass
3.	Evergreen needle leaf tree
4.	Deciduous needle leaf tree
5.	Deciduous broad leaf tree
6.	Evergreen broad leaf 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

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	0.80
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	0.06	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

*See definitions in Table 1.

**Soil depths in code are in mm as are all water storages to make the conversion factor 1.0 between water amounts and SI energy fluxes.

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) Moisture content relative to saturation at which transpiration ceases	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

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

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.

In the model, the vegetative types, along with soil moisture and season, determine the (i) fractional vegetative cover over a grid square, (ii) plant and soil albedos, (iii) surface roughness, and (iv) soil thermal and hydrologic properties.

3.2 Drag Coefficients

In the BATS drag coefficient C_D is calculated as,

$$C_D = f(C_{DN}, Ri_B), \tag{5}$$

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

$$Ri_B = \frac{gz_1(1 - T_{g1}/T_a)}{V_a^2} \tag{6}$$

where $V_a^2 = u_1^2 + v_1^2 + U_c^2$ with T_{g1} the surface soil (or snow or ice) temperature and T_1, u_1, v_1 the air temperature $\times (p_s/p_1)^{\varkappa}$ and wind components at z_1, where z_1 is the height of the lowest model level, g = acceleration due to gravity, and

$$U_c = 0.1 \text{ ms}^{-1}, \text{ if } T_{g1}/T_1 < 1 \tag{7}$$

$$= 1.0 \text{ ms}^{-1}, \text{ if } T_{g1}/T_1 > 1$$

For $Ri_B < 0$

$$C_D = C_{DN} \ (1 + 24.5(-C_{DN} Ri_B)^{1/2}) \tag{8}$$

and for $Ri_B > 0$

$$C_D = C_{DN}/(1 + 11.5 \ Ri_B) \tag{9}$$

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 as

$$C_{DN} = \left[\frac{k}{\ln(z_1/z_o)}\right]^2, \tag{10}$$

where k = 0.40, von Karman constant, and z_o is the roughness length. For water surface, we take $z_o = 2.3 \times 10^{-4}$ m so that C_{DNW} = 0.0014. For bare land, we take $z_o = 10^{-2}$ m so that $C_{DNL} = 2.4 C_{DNW}$.

(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, i.e., $C_{D,FN}$ denotes the neutral drag coefficient over the grid square, then

$$C_{D,FN} = \sigma_f C_{FN} + (1 - \sigma_f)(S_{cv} C_{DNW} + (1 - S_{cv}) C_{DNL}), \tag{11}$$

where C_{FN} is the local drag coefficient over vegetation, determined using Eq. (10) and $z_o = z_{ov}$ tabulated for the given vegetation type, and S_{cv} is the fraction of ground covered by snow. The vegetation fraction is corrected for snow covering vegetation as follows:

$$\sigma_f = (1 - W_T)\, \sigma_{fo}, \tag{12}$$

where σ_{fo} is the fraction of vegetation in the absence of snow and

$$W_T = W_{To}/(1 + W_{To}) \tag{13}$$

$$W_{To} = \text{snow depth} \,/\, (10 . z_{ov}) \tag{14}$$

The term S_{cv} is calculated from $S_{cv} = S_{cvo}/(1+S_{cvo})$, S_{cvo} = snow depth/(0.1 m). Snow depth is calculated from the liquid-water content of snow divided by the model-calculated snow density. These formulae are based on the assumption that half the vegetation is covered by snow for snow depth of 10 z_{ov}, as in (14), and half of bare ground for a snow depth of 0.01 m, assuming $z_{ov} >> 0.01$ m, as it is for the input data.

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.

For lead factors for sea ice, it is assumed

a = 0.02 for Arctic, latitude < 80°N,

a = 0.01 for 80° - 85°N and a = 0.005 within 5° of the North Pole, and

a = 0.04 for Antarctica

Observations have indicated that Arctic sea ice is more compact than Antarctic sea ice.

3.3 Albedo

(a) Vegetation and soil albedos

Reflection of solar radiation is a strong function of wavelength for many surfaces. Also, the spectrum of solar radiation reaching the surface depends strongly on the optical properties of the atmosphere. Therefore, use of spectrally integrated surface albedos may be too inaccurate. BATS radiative calculations use a crude spectral decomposition of solar radiation by distinguishing between wavelengths shorter than or longer than 0.7 μm. Plants, in particular, have much lower albedos for visible than for near-infrared solar radiation, because they need the visible radiation for photosynthesis but, otherwise, must avoid overheating. By contrast, snow has much higher visible than near-infrared albedos; and these albedos depend significantly on solar zenith angles. The computation of surface albedos, and hence absorbed solar radiation, is handled externally to the rest of the BATS package in subroutine ALBEDO which is linked to the radiation scheme in the CCM. Snow, if present, is also considered because of its highly variable albedo and because vegetation can 'mask' the snow surface. The albedo of snow is parameterized by a measure of snow age.

For each of the land grid points, three types of albedos are defined in subroutine ALBEDO - visible solar albedo of vegetation (λ < 0.7 μm), near-infrared albedo of vegetation (λ > 0.7 μm), and soil albedo. The detailed distributions of the soil albedo depend upon soil type and soil wetness. However, for vegetation cover σ_f of 0.80 or more, relatively little short-wave radiation reaches the ground so that these parameterizations become secondary. The values for vegetation albedo used in subroutine ALBEDO are listed in Table 2.

The albedo for bare soil A_{LBG} is taken to be,

$$A_{LBG} = A_{LBGO} + \Delta\alpha_g(S_{sw}), \tag{15}$$

where A_{LBGO} is the albedo for a saturated soil and where the increase of albedo due to dryness of surface soil is given for $\lambda < 0.7\ \mu m$ as a function of the ratio of surface soil water content S_{sw} to the top layer depth Z_1,

$$\Delta\alpha_g\ (S_{sw}) = 0.01\ (11 - 40\ S_{sw}/Z_1) > 0 \tag{16}$$

This formulation is chosen so that soil albedos range in a nonlinear fashion between the saturated and dry values given in Table 3. The term S_{sw} becomes small ($\leq$ 0.03m) before the soil albedo shows a significant increase. Moisture is retained around the soil grains until ~ 80% dryness occurs. The soil albedos for $\lambda > 0.7\ \mu m$ are twice those for $\lambda < 0.7\ \mu m$. Dry and saturated soil albedos for the eight colour classes are shown in Table 3.

(b) Snow albedos

Snow albedos are determined from the following equations:

$$\alpha_V = \alpha_{VD} + 0.4\ f(ZEN)[1 - \alpha_{VD}] \tag{17}$$

$$\alpha_{IR} = \alpha_{IRD} + 0.4\ f(ZEN)[1 - \alpha_{IRD}] \tag{18}$$

where α_V = albedo for $\lambda < 0.7\ \mu m$, α_{IR} = albedo for $\lambda > 0.7\ \mu m$, and the subscript D denotes diffuse albedos as given by:

$$\alpha_{VD} = [1 - C_S\ F_{AGE}]\ \alpha_{VO} \tag{19}$$

$$\alpha_{IRD} = [1 - C_N\ F_{AGE}]\ \alpha_{IRO} \tag{20}$$

$$C_S = 0.2,\ C_N = 0.5, \tag{21}$$

and

α_{VO} = 0.95, the albedo for visible radiation incident on new snow with solar zenith angle less than 60°

α_{IRO} = 0.65, the albedo of new snow for near-infrared solar radiation with solar zenith angle less than 60°

$f(ZEN)$ = factor between 0.0 and 1.0 giving increase of snow visible albedo due to solar zenith angle exceeding 60°

$C(ZEN)$ = cosine of the solar zenith angle

F_{AGE} = a transformed snow age defined below and used in this section to give the fractional reduction of snow albedo due to snow aging for solar zenith angle less than 60°

The following parameterizations are used:

$$f(ZEN) = \frac{1}{b}\left[\frac{b+1}{1+2b\,C(ZEN)} - 1\right], \tag{22}$$

$$f(ZEN) = 0, \text{ if } C(ZEN) > 0.5$$

Equation has the property for all b that it vanishes at C(ZEN) = 0.5 and is unity at C(ZEN) = 0 (sun on the horizon); b is adjustable to best available data - for now b = 2.0.

Snow albedo decreases with time due to growth of snow grain size and accumulation of dirt and soot. The decrease term F_{AGE} is parameterized by:

$$F_{AGE} = \tau_{SNOW}/[1 + \tau_{SNOW}] \tag{23}$$

The nondimensional age of snow τ_{SNOW} is incremented as follows:

$$\Delta\tau_{SNOW} = \tau^{-1}(r_1 + r_2 + r_3)\,\Delta t, \tag{24}$$

where $\tau_0 = 1 \times 10^{-6}\ s^{-1}$

$$r_1 = \exp\ 5000(\ 1/273.13\ -\ 1/T_{g1}) \tag{25}$$

$$r_2 = r_1^{10} \leq 1 \tag{26}$$

and

$$r_3 = 0.01 \text{ over Antarctica}, \quad = 0.3 \text{ elsewhere.}$$

The term r_1 represents the effect of grain growth due to vapour diffusion, the temperature dependence being essentially proportional to the vapour pressure of water.

The term r_2 represents the additional effect near and at freezing of melt water and r_3 the effect of dirt and soot.

A snowfall of 0.01 m liquid water is assumed to restore the surface age, hence albedo, to that of new snow. Since the precipitation in one model time step will generally be less than that required to so restore the surface when it snows for a given time step, the snow age is reduced by a factor depending on the amount of the fresh snow in m, ΔP_s, as follows:

$$\tau^{N+1}_{SNOW} = (\tau^{N}_{SNOW} + \Delta\tau_{SNOW})(1 - 100\ \Delta P_s)\tau_{SNOW} > 0, \tag{27}$$

where $\Delta\tau_{SNOW}$ is defined in Eq. (24).

3.4 Precipitation

The precipitation taken in the model can be either rain or snow. 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.

$$P_s = P,\ P_r = 0, \qquad \text{if } T_1 \leq T_c \tag{28}$$

$$P_s = 0,\ P_r = P, \qquad \text{if } T_1 > T_c \tag{29}$$

3.5 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}.

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 σ_f,

$$L_{AI} = L_{AI}^{MIN} + F_{SEAS}\,(T_{g2}) \times (L_{AI}^{MAX} - L_{AI}^{MIN}) \tag{30}$$

where the seasonal factor $F_{SEAS}(T)$ is defined by

$$F_{SEAS}\,(T) = 1 - 0.0016 \times (298.0 - T)^2 \tag{31}$$

It ranges from 1.0 at 298.0 K to 0.0 at 273.0 K and 323 K.

The sum of L_{AI} and S_{AI} the L_{SAI} (leaf stem area index is $L_{SAI} = L_{AI} + S_{AI}$. To include evaporation from wetted stems and leaves the fractional area of the leaves covered by water is defined as

$$L_W = \left(\frac{W_{dew}}{W_{DMAX}} \right)^{2/3} \tag{32}$$

where W_{dew} is the total water intercepted by the canopy and W_{DMAX} is the maximum water the canopy can hold. The same expression is used for the stems. The fraction L_d of foliage surface free to transpire is then defined by

$$L_d = (1.0 - L_w)\, L_{AI} / L_{SAI} \tag{33}$$

The values presently used for defining L_{AI} and S_{AI} are listed in the land cover type parameter list .

Also needed is the magnitude of wind within the foliage layer taken to be

$$U_{af} = V_a\, C_D^{1/2} \tag{34}$$

3.6 Interception

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 re-evaporate to the air, but at the same time transpiration is suppressed over wet green leaves. Similarly, the formation of nighttime dew can keep foliage cool in the morning and suppress transpiration. Typical values for re-evaporation 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 $\times$ 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, i.e.,

$$\frac{\partial W_{dew}}{\partial t} = \sigma_f P - E_f + E_{tr} \tag{35}$$

If $W_{dew} > W_{DMAX} = 0.0002 \text{ m} \times \sigma_f L_{SAI}$, then W_{dew} is set equal to

W_{DMAX} and the excess leaf moisture is added to the precipitation on the soil, either as water or snow depending on whether or not the snowfall criteria are satisfied.

3.7 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

$$F_q = \text{minimum of } (F_{qp}, F_{qm}) \tag{36}$$

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} is calculated from

$$F_q = \rho_a \, C_D \, V_a \, (q_g - q_a) \tag{37}$$

where ρ_a is the surface air density, C_D the aerodynamic drag coefficient for heat, C_p the specific heat for air, V_a the wind speed, q_g the saturated mixing ratio at the temperature of the surface, q_a the mixing ratio of the model lowest level and,

$$F_{qm} = C_k \, D \, s_o / \, (Z_o \, Z_1)^{1/2} \tag{38}$$

where Z_o is the depth of the total soil active layer (between 0.5 and 2m), Z_1 the depth of surface soil layer (restricted to be between 1 and 20 cm thickness), and D is an average soil diffusivity defined by

$$D = 1.02 \, D_{max} \, s_1^B \, s_o^2 \, (s_o/s_1)^B f \tag{39}$$

using $$D_{max} = B\,\emptyset_o\,K_o/\rho_{wm} \tag{40}$$

where ρ_{wm} is the fraction of saturated soil filled by water and K_o and $\emptyset_o$ the maximum conductivity and soil suction given in Table 3, B is defined as

$$B_f = 5.5 - 0.8B\,[1 + 0.1(B-4)\,\log_{10}\,(K_o/K_R)] \tag{41}$$

with $K_R = 10^{-5}$ ms^{-1}. C_k is given by

$$C_k = (1 + 1550\,D_{min}/D_{max})\,[\frac{B-3.7 + 5/B}{B+5}] \tag{42}$$

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. The proportionality factor is the ratio of water contents within these layers i.e. $(s_1 Z_1/s_o Z_o)$. The down gradient rate of transfer of water from the lower soil layer to the surface layer, Y_w, is

$$Y_w = Y_{wo} = C_k\,D\,(s_o - \varepsilon\,s_1)/(Z_o Z_1)^{1/2} \tag{43}$$

where $\varepsilon = Z_1/Z_o$. Eq. (43) works well for assumed regime of daily evaporation but gives unrealistic results during infiltration when s_1 exceeds so. With infiltration, it is more realistic to assume that the downward transfer by diffusion is proportional to $(s_o - s_1)$.

To interpolate between these limits it is assumed

$$\varepsilon = \frac{Z_1/Z_o}{\text{max.of}(Z_1/Z_o \text{ or}(1-s_1/s_o) \div (1-s_1/s_o))} \tag{44}$$

where s_1/s_o is the ratio of s_1 to s_o during evaporation with a self similar profile. For simplicity, B=5, $K_o=10^{-5}\,ms^{-1}$, $\hat{Z}_1=0.1$ and $\hat{Z}_o=1$ are taken, giving $s_1/s_o=0.8$. The model water transfer between layers is evaluated including an additional gravitational drainage term

$$Y_w = Y_{wo} - (s_1/s_o)^{B+1.5} R_g \tag{45}$$

where R_g is defined as Eq.(67) in section 3.9. For the value of s at the interface between the upper and lower layer the geometric mean of s_1 and s_o has been assumed. The possibility of a gradient-driven upward water flow from an underlying saturated zone is neglected. Using eqns. for defining Y_w, water in the surface layer is generally transferred downward as rapidly as generated by rainfall of GCM grid square intensity, for soil other than heavy clay. Hence water does not pond very frequently on the surface from saturation of the surface layer. It is thus necessary to assume additional surface runoff near saturation, tuned to get the observed surface runoff, or to assume a sub-grid scale variation of rainfall intensity.

3.8 Evapotranspiration and Evaporation from Vegetation

3.8.1 EVAPORATION FROM WET FOLIAGE

The water flux from dry foliage follows similar considerations but, in addition, the resistance to water flux by stomata needs consideration. The water on wet foliage (leaves and stems) evaporates according to

$$E_f^{WET} = A_f\, \rho_a\, r_{la}^{-1}\, (q_f^{SAT} - q_{af}) \,, \tag{46}$$

where A_f is the projected area of the wet surface, which for the whole wet canopy is $\sigma_f \times L_{SAI}$, q_f^{SAT} is the saturation water vapour mixing ratio at temperature of the foliage T_f, q_{af} is the water vapour mixing ratio of air within the canopy, and r_{la} is the aerodynamic resistance to moisture and heat flux of the foliage molecular boundary layer per unit foliage projected area. Eq. (41), if negative, gives the rate of accumulation of dew on foliage whether wet or not.

The conductance for heat and vapour flux from leaves is given by

$$r_{la}^{-1} = C_f \times (U_{af} / D_f)^{1/2} \tag{47}$$

where $C_f = 0.01\ \mathrm{m\ s}^{-1/2}$, D_f is the characteristic dimension of the leaves in the direction of wind flow, and U_{af} is the magnitude of the wind velocity incident on the leaves. Eq. (46) gives the evaporation at each surface within the canopy; however, a different definition of Eq. (47) would be needed to apply it to stems and needles. It is also assumed that Eq. (46) can be applied to the canopy as a whole.

The heat flux from the foliage is given by

$$H_f = \sigma_f L_{SAI}\, r_{la}^{-1} \rho_a C_p (T_f - T_{af}) \tag{48}$$

3.8.2 EVAPORATION FROM PARTIALLY WET FOLIAGE

The flux E_f from foliage that is only partly wet, with wetted fraction denoted L_w, follows from Eq. (46) as

$$E_f = r'' E_f^{WET} \tag{49}$$

where

$$r'' = 1 - \delta (E_f^{WET}) [1.0 - L_w - L_d (\frac{r_{la}}{r_{la} + r_s})] \tag{50}$$

where r_s = stomatal resistance to be discussed further and where δ is a step function and is one for positive argument and zero for negative argument. The fraction of wetted area over nontranspiring foliage is assumed to be the same as that for transpiring foliage.

Transpiration E_{tr} occurs only from dry leaf surfaces and is only outward,

$$E_{tr} = \delta (E_f^{WET}) L_d \left(\frac{r_{la}}{r_{la} + r_s}\right) E_f^{WET} \tag{51}$$

The above formulation neglects the likely small temperature differences between wet and dry surfaces, as well as the effects of several other possible inhomogeneities. For example, many plants, such as hardwood trees, have leaf stomata that occur only on the underside of leaves, whereas leaf water may be stored largely on the upper surface of the leaves.

3.8.3 ENERGY BALANCE OF PLANT CANOPY AND SOIL

The air within the canopy has negligible heat capacity and so heat flux from the foliage H_f and from the ground H_g must be balanced by heat flux to the atmosphere H_a, i.e.,

$$H_a = H_f + H_g \tag{52}$$

where flux to the atmosphere is given by

$$H_a = \rho_a C_p C_D V_a (T_{af} - T_a) \tag{53}$$

where C_p is the specific heat of air, V_a is the magnitude of atmospheric wind above the canopy, and C_D is the aerodynamic bulk transfer coefficient between canopy air and atmosphere above, assumed to be the same for heat and moisture as for momentum. The flux from the ground is assumed to be

$$H_g = \rho_a C_p C_D [(1 - \sigma_f) V_a + \sigma_f U_{af}](T_{g1} - T_{af}) \tag{54}$$

Eqs. (52) - (54) are solved for T_{af}, i.e.,

$$T_{af} = (c_A T_a + c_F T_f + c_G T_{g1})/(c_A + c_F + c_G) \tag{55}$$

where

$$c_A = c_D V_a \tag{56}$$

$$c = \sigma_F L_f r_{SAI}^{-1} \, {}^{\prime} la \tag{57}$$

$$c_G = C_D[(1 - \sigma_f)V_a + \sigma_f U_{af}] \tag{58}$$

are conductances for heat flux, to the atmosphere above the canopy, and from foliage, and the ground, respectively. Similarly, the canopy air is assumed to have zero capacity for water vapor storage so that the flux of water from the canopy air E_a balances the flux from the foliage E_f and the flux from the ground, E_g, i.e.,

$$E_a = E_f + E_g \tag{59}$$

where E_f was defined eariier in Eq. (49), and

$$E_a = \rho_a c_A (q_{af} - q_a) \tag{60}$$

$$E_g = \rho_a c_G f_g (q_{g,s} - q_{af}) \tag{61}$$

where $q_{g,s}$ is the saturated ground water vapour concentration and f_g is a wetness factor, defined as the ratio of actual to potential ground evaporation as obtained from the soil moisture parameterization. Eq. (59) is solved for q_{af} using the definition of E_a, E_f, E_g, i.e.,

$$q_{af} = (c_A q_a + c_V q_f^{SAT} + c_G f_g q_{g,s}) \div (c_A + c_V + f_g c_G), \tag{62}$$

taking

$$c_H = c_F / (c_A + c_F + c_G) \tag{63}$$

After completion of the T_f calculation, the following terms are obtained,

$$\Delta T_{a,f} = T_a - T_{af} \; , \qquad \Delta q_{a,f} = q_a - q_{af} \; . \tag{64}$$

for use in obtaining sensible and latent heat fluxes to the atmosphere, and updating the leaf water budget by adding the difference between the foliage evapotranspiration and its water vapor flux to the atmosphere. Leaf water can either increase because of dew formation or decrease because of evaporation of leaf water.

3.9 Infiltration and Percolation to Ground Water

Moisture incident on the ground either infiltrates the soil or is lost to surface runoff.

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)

$$\emptyset = \emptyset_o \, s^{-B} \tag{65}$$

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

$$D = - K_w \, \partial\emptyset/\partial s = K_{wo} \, B \, s^{B+2} \tag{66}$$

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

$$R_g = K_{wo} \, s^{2B+3} \tag{67}$$

3.10 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. It is given by

$$R_s = (\rho_w/\rho_{wsat})^4\ G \quad , \quad T_{g2} \geq 0°C$$

$$= (\rho_w/\rho_{wsat})\ G \quad , \quad T_{g2} < 0°C \tag{68}$$

where ρ_{wsat} is the saturated soil water density and ρ_w the soil water density weighted toward the top layer as defined by

$$\rho_w = \rho_{wsat} \frac{(s_o + s_1)}{2} \tag{69}$$

and G is the net water applied to the surface defined in next section (Eq.(72)).

3.11 Soil Moisture

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

$$\frac{\partial S_{sw}}{\partial t} = G - R_s + Y_w \tag{70}$$

$$\frac{\partial S_{tw}}{\partial t} = G - R_s + R_g \tag{71}$$

where $$G = P_r + S_m - F_q \tag{72}$$

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).

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 surface soil temperature and vice-versa.

3.12 Soil Temperature

In direct analogy to the study of need of dynamics which govern the movement of water in the soil, there is also a need to understand heat conduction in the soil.

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 sub surface and conductive gain from upper layer based on linear damping. The soil and subsoil temperature are obtained from

$$\frac{\partial T_{g1}}{\partial t} = \frac{c_1 h_s}{\rho_s c_s d_1} - \frac{c_2 (T_{g1} - T_{g2})}{\tau_1} \qquad (73)$$

$$\frac{\partial T_{g2}}{\partial t} = - c_3 \left[\frac{(T_{g2} - T_{g1})}{\tau_1} + c_4 (T_{g2} - T_{g3}) + Q_{sf} \right] \qquad (74)$$

where

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

T_{g2} = Sub surface 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 = $(S_g + (F_{IR}^{\downarrow} - F_{IR}^{\uparrow}) - F_s - L_{v,s} F_q - L_f S_m - L_f W_{m1})$ (75)

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.

$F_{\downarrow IR} - F_{\uparrow IR}$ = 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 sub surface soil water

$\rho_s c_s$ = Specific heat of sub surface 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. (73), (74) and (75) use diurnal cycle of soil heating. The heat required for melting (freezing) ground to be used in eqn. (73) - (75) is zero if $T \geq T_m$ (melting or freezing temp. of pure water = 273.16 k) or $T \leq T_m - 4°$. Otherwise

$$W_{m1} = 0.25\ (S_{sw} - F_{ru})\ \frac{\partial T_{g1}}{\partial t}\ , \qquad S_{sw} > F_{ru} \qquad (76)$$

$$W_{m2} = 0.25\ (S_{tw} - S_{sw} + F_{ru} - F_{ra})\ \frac{\partial T_{g2}}{\partial t}\ , \quad S_{tw} - S_{sw}/(F_{ra} - F_{ru}) \qquad (77)$$

where F_{ru} and F_{ra} are the water in the upper and lower soil layers respectively.

Eqns. (73) and (74) are solved using finite difference technique. The implementation of these equations depends upon the surface type as follows:

3.12.1 BARE SOIL SURFACE

Thermal conductivity and heat capacity of the soil depend upon the moisture and organic content of the soil. For a loam soil the following approximate formula is inferred

$$\rho_s c_s = (0.23 + \rho_w) c_w \qquad (78)$$

$$k = \lambda_s / (0.23 + \rho_w) \qquad (79)$$

$$\lambda_{sl} = \frac{(2.9\ \rho_w + 0.04)\ \lambda_c}{(1 - 0.6 \times \rho_w)\rho_w + 0.09} \qquad (80)$$

where $\lambda_c = 10^{-6} m^2 s^{-1}$, ρ_w is the volume of liquid water per unit volume of soil and $c_w = 4.186 \times 10^6\ J\ m^{-3} k^{-1}$ is the specific heat of water. From this formula, the thermal conductivity of all soil types is given by

$$\lambda_s = S^i_{KRAT} \times \lambda_{sl} \qquad (81)$$

where S^i_{KRAT} = is the ratio of the thermal conductivity of texture type i to that of loam.

3.12.2 SNOW COVERED LAND

For snow covered land the computation is similar to bare soil, the difference being in constants only

$$k_s = k_{so}\ \rho_{sw} \qquad (82)$$

where $k_{so} = (7.0 \times 10^{-7}/0.49) m^2 s^{-1}$

$$\rho_s c_s = \rho_{sw}\ c_{sw} \qquad (83)$$

where $c_{sw} = 0.49\ c_w \qquad (84)$

is the specific heat of snow for unit snow density, numerically equal to the specific heat of ice per unit mass and ρ_{sw} is the density of the snow relative to water which is a function of snow age factor. Typically, for fresh snow $\rho_{sw} = 0.1$ and for $\rho_{sw} = 0.3$

For fractional bare ground, weighted means of snow and ground conductivities and of heat capacities are used.

$$k_s = \frac{d_s k_{s\ snow} + k_{s\ ground}}{1 + d_s} \qquad (85)$$

where $d_s = 10\ S_{cv}/\rho_{sw}$ and S_{cv} is the snow cover (liquid water equivalent in m).

3.12.3 BARE SEA-ICE OR SNOW COVERED SEA-ICE

The diurnal component of heat storage within the ice is neglected and replaced by steady conduction of heat from the underlying ocean and hence

$$\frac{\partial T_g}{\partial t} = \frac{h_s}{[0.5(c_{sw}S_{cv} + w_t c_i d_{ice}]} \qquad (86)$$

where the square bracketed term is an effective heat capacity of snow and ice.

$c_i = 0.45\ c_w$ and d_{ice} the depth of ice, specified as a function of season or computed, and $w_t = 1.4\ \rho_{sw} d_{ice} / (S_{cv} + 1.4\ \rho_{sw} d_{ice})$

$$h_s = S_g + F_{IR}^{\downarrow} - F_{IR}^{\uparrow} - F_s - L_v F_g - L_f S_m + F_c \qquad (87)$$

The heat conduction through snow covered sea ice or bare sea ice is given by:

$$F_c = \frac{K_{snow}(T_B - T_g)}{1 + (K_{snow}/K_{ice})} \qquad (88)$$

where

$$K_{snow} = k_s \rho_{sw}^2 c_{sw}/S_{cv}$$

$$K_{snow}/K_{ice} = 1.4 \rho_{sw}^2 d_{ice}/S_{cv}$$

T_B = −1.8°C approximate freezing point of sea ice.

3.13 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.

The stomatal resistance factor is taken to be

$$r_s = r_{smin} \times R_l \times S_l \times M_l \tag{89}$$

R_l gives the dependence of r_s on solar radiation. The factor R_l varies between about 1 for overhead sun and r_{smax}/r_{smin} for night time, where r_{smax} is the cuticular resistance of the leaves. It is assumed to be of the form

$$R_l = \frac{1 + f}{f + r_{smin}/r_{smax}} \tag{90}$$

where $f = F_v/F_{vc}$ with $r_{smax} = 5000\ s\ m^{-1}$, F_v = flux of visible solar radiation, and F_{vc} the visible solar flux for which R_l is about double its minimum value. Present model values are F_{ve}=30

Wm^{-2} for trees, and F_{vc}=100 Wm^{-2} for grasslands and crops. The dependence of stomatal resistance on vapor pressure deficit is not included because it appears to be highly variable from species to species. Hence, r_{smin} , which takes different values for different kinds of vegetative cover, is intended to apply for average vapour pressure deficit conditions.

Eq. (90) is averaged over the different leaves in the canopy which receive different amounts of radiation. The canopy is divided into an upper and lower fraction and it is assumed that 0.75 of the radiation is absorbed by the upper canopy and 0.25 is absorbed by the lower canopy, and that the leaf stem area indexes of upper (L_{SAIU}) and lower (L_{SAIL}) canopy are each one half of the total leaf stem area index, i.e., $L_{SAIU} = L_{SAIL} = 0.5L_{SAI}$, and hence

$$F_{vu} = 0.75\, F_{vi} / L_{SAIU} \tag{91}$$

$$F_{vl} = 0.25\, F_{vi} / L_{SAIL} \tag{92}$$

where F_{vi} is the visible radiation incident at the top of the canopy. Eq. (90) is applied using F_{vu} and then F_{vi} for F_v and the resulting conductivities averaged to get R_l in the model.

The seasonal temperature factor $S_l = F_{SEAS}(T_f)$.The moisture factor M_l depends on the soil moisture and the ability of plant roots to take water readily from the soil for a given level of root moisture. Initially, M_l=1, and if the plants' transpiration exceeds a maximum value, depending on soil moisture as described below, M_l is increased so that the transpiration is maintained at the maximum value. Finally, if r_s as given by Eq. (89) exceeds r_{smax}, it is set to r_{smax}.

3.14 Root Resistance

The transpiration rate calculated from Eq. (51) must be consistent with the maximum transpiration that the vegetation can sustain as defined below. If E_{tr} is found to exceed E_{trmx}, then r_s

is redetermined so that $E_{tr} = E_{trmx}$, the maximum transpiration available from the plant. The plant water uptake in each soil layer is 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. Lumping various terms together yields the following formula.

$$E_{trmx} \quad Y_{ro} \sum_i R_{ti}(1 - W^i_{LT}) \tag{93}$$

where Y_{ro} is the maximum transpiration that can be sustained. The sum is over soil layers, each designated by subscript i, R_{ti} is the fraction of roots in a given soil layer, and W^i_{LT} is a soil dryness (or plant wilting) factor. Hence Y_{ro} is taken as, $Y_{ro} = 2\times10^{-7}$ ms^{-1} $\times\ \sigma_f \times S_{EASB}$, where S_{EASB} is a factor that is 1 during the growing season and drops to 0 when the soil is frozen. For typical vegetation, σ_f=0.8, and close to field capacity, W^i_{LT}=0.05 so that typically for well watered growing season vegetation, $Y_{ro}=1.5\times10^{-7}$ ms^{-1}, corresponding to a maximum latent energy flux of about 380 W m^{-2}. Observed latent fluxes from unwetted foliage under intense solar radiation rarely exceed 400 Wm^{-2}.

The negative of the leaf potential can be approximated by the maximum value it takes before leaf desiccation, since the leaf potentials of many plants approach this value under any significant water stress. The term W^i_{LT} then is $(\O-\O o)$ divided by $(\O_{max}-\O_o)$, where $\O$ is the soil water suction and $\O_{max}$ is the maximum value of negative of potential of leaves before desiccation. Hence, for soil suction of the form given in section 3.9

$$W^i_{LT} = \frac{s_i^{-B} - 1}{s_w^{-B} - 1} \tag{94}$$

where s_i is the soil water of the ith layer and s_w the soil water for which transpiration goes to zero. The current model value is s_w=0.125. Normally, soils of clay-like texture would have larger values and sandy - textured soils lower values. The factor W^i_{LT} ranges from 0 at saturation to 1 at the "permanent wilting point".

The ratio of maximum water extraction, given by Eq. (93) for a given soil layer, to the maximum water extraction for the total active soil layer multiplied by the fraction of roots in the given layer gives the fraction of total transpiration that is taken from the given layer.

3.15 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.

In snowing case or in presence of snow cover or, it is checked if T_g is 0.0°C. If it is so, snowmelt rate is computed first before computing surface temperature. The snowmelt rate S^N_m, when positive, is given by

$$S^N_m = L_f^{-1} \times [h^N_s - G_{HEAT}] \tag{95}$$

where $$h^N_s = S_g + F^{\downarrow}_{IR} - F^{\uparrow}_{IR} - F_s - L_s F_q$$

and where G_{HEAT} is the heat conduction to the underlying reservoir, which is either snow or ground depending on snow depth that is consistent with Eq.(73),

$$G_{HEAT} = c_2 \rho_s c_s d_1 \; [(T_{g1} - T_{g2})/c_1 \tau_1) \tag{96}$$

T_g is taken to be 0.0°C in calculating F_s and F_q over melting snow.

If calculated S_m exceeds snow cover S_m is set to the snow cover and ground temperature is calculated from eqns. (73), (75).

If snow remains after melting the snow amount given by Eq.(95) T_g is set equal to zero. The snow cover is updated from

$$\frac{\partial S_{cv}}{\partial t} = P_s - F_q - S_m \qquad (97)$$

where S_{cv} is the snow cover measured in terms of liquid water content, P_s the snow precipitation rate and F_q the rate of sublimation.

3.15.1 SENSIBLE AND LATENT HEAT FLUXES OVER ICE OR A BARE SURFACE

The sensible and latent heat fluxes over water, sea ice, or bare surfaces are obtained using momentum drag coefficients obtained in the previous section as follows:

$$F_s = \rho_a C_p C_D V_a \left(T_{g1} - T_a\right) \qquad (98)$$

where ρ_a is the surface air density, C_D the aerodynamic drag coefficient for heat ,C_p the specific heat for air, and V_a the wind speed. Similarly, the moisture flux (from the surface) to the atmosphere F_q is given by

$$F_q = \rho_a C_D V_a f_g (q_g - q_a) \qquad (99)$$

where q_g is the saturated mixing ratio at the temperature of the surface (ground, snow, ice ,or water) , q_a the mixing ratio of the model lowest level, and f_g the wetness factor, which has the value of 1.0 except for diffusion limited soil surfaces , where it is defined by the ratio of actual to potential ground evaporation, i.e.,

$$f_g = F_q / F_{qp} \qquad (100)$$

3.15.2 SOIL MOISTURE AND SNOW COVER WITH VEGETATION

Finally, we note that, in the presence of vegetation the soil moisture and snow cover, Eqs. (70), (71) and (97) become

$$\frac{\partial s_{sw}}{\partial t} = P_r(1 - \sigma_f) - R_s + Y_w - \beta E_{tr} - F_q + S_m + D_w \qquad (101)$$

$$\frac{\partial s_{tw}}{\partial t} = P_r(1 - \sigma_f) - R_w - E_{tr} - F_q + S_m + D_w \qquad (102)$$

$$\frac{\partial s_{cv}}{\partial t} = P_s(1 - \sigma_f) - F_q - S_m + D_s \qquad (103)$$

where 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, as mentioned following Eq. (35), and R_w=R_s+R_g is the total runoff.

4.0 BATS PROGRAM

4.1 Program Description

The model described here is the BATS 1E version developed by R E Dickinson and P J Kennedy with contributions from K Blumel, F Giorgi and A H Sellers. It greatly modifies the previous versions in general cleanup and stabilization of iterations; three layer soil moisture; improvement and bug fixes by Bluemel including an improved canopy model; improvement in soil temperature force-restore method overlying snow; stomatal resistance dependence on solar radiation made dependent on LAI; inclusion of a non-zero displacement level; elimination of soil water movement in frozen ground; fixing of fatal errors in carbon routine; and derivation of leaf iteration scheme.

It also adds a dependence of stomatal resistance on vapour pressure deficit, allowing for soalr zenith dependence of incident light in calculating dependence of stomatal resistance on light; further streamlining the iterative calculation of leaf temperature. This version redefines output fluxes of sensible and latent heat to agree exactly with those used for soil canopy balance to ensure conservation of energy. Latent heat of sublimation now applies to all soil terms where snow covered or below freezing. Leaf temperature calculations are reformulated to use average longwave rather than over bare soil as done previously.

4.1.1 MAIN DRIVE PROGRAM

The model is basically designed to couple to a large scale meteorological model. Some of its structures, in particular, the C array for constants and the representation of the primary variables in the F array with their location by pointers, as well as some cgs units, are carryovers from the NCAR 3rd generation GCM. The core model, which begins with subroutine BNDRY, is here driven by a skeleton interface consisting of the below DRIVER routine, the input routines here initialize 6 sample grid points which .are somewhat arbitrarily identified with geographical locations. These are -

1. Equatorial Forest
2. Desert
3. Coniferous Forest
4. Tundra/Taiga
5. Grazing Grassland
6. Arctic Sea Ice

However, the model can recognize for 18 land types given in Table 1 (including the above six types).

4.1.2 SUBROUTINES USED IN THE MODEL

BLOCK DATA: This assigns constants that appear in common blocks of the program. The land/vegetation parameters given in Table 2 are included in BLOCK DATA. Besides these the data on depths of upper soil layer (DEPUV), rooting zone soil layer (DEPRV) and total soil layer (DEPTV) are also given here. DEPUV and DEPTV are taken to 100 mm and 1000 mm for all 18 land types and, DEPRV depends on the type of vegetation.

BDCON: This subroutine defines constants for boundary subroutine that are not set in BLOCK DATA. The constants are:

PI = 3.141592
MHIS = 48; (Iterations in one day, assuming 1/2 hour time step)

Specific heats (Joules/m**3/K):
CH2O = 4.186E6
CICE = 0.45*CH2O

CWI = 1./0.45

Specific heat for snow after multiplied by snow density:

CSNW = 0.49*CH2O

CWS = 1./0.49

Data for vegetation calculation:

Maximum stomatal resistance (S/m):

RMAXO = 2.E4

Maximum allowed dew (mm) and inverse (DEWMXI)

DEWMX = 0.1

DEWMXI = 1.0/DEWMX

Maximum rate of transpiration with saturated soil (Kg/m**2/s):

TRSMXO = 2.E-4

Drain is drainage out of 10m layer bottom (mm/s); it is set fairly large to prevent swamping the soil:

DRAIN = 4.E-4

Length of day in seconds:

TAU1 = 8.64E4

Time step - presently set at half an hour = C(4), Inverse of C(4) is C(7)

C(6) = 3600

C(4) = 0.5*C(6)

C(7) = 1./C(6)

Gravity (m/s**2):

C(54) = 9.80616

Gas constant for dry air (J/Kg/K):

C(57) = 2.8704E2

Specific heat at constant pressure for dry air (CPD):

C(58) = 3.5*C(57)

Ratio of RD/CPD is kappa - comes into definition of potential temperature:

C(68) = C(57)/C(58)

Freezing point value:

C(67) = 273.16

SI//non-D constants for Tetens formula - used in subroutine SATUR which computes specific humidity QSAT which is nondimensional:

C(70) = 21.874

C(71) = 7.66

C(72) = 17.269

C(73) = 35.86

C(74) = 6.11E2

C(75) = 0.622

C(76) = 0.378

Standard pressure (pa):

C(81) = 1.013250E5

Stefans constant (Watts/m**2/K**4):

C(83) = 5.67E-8

Turbulent wind for stable conditions (m/s):

C(90) = 0.1

Latent heats (Joules/kg):

C(125) = 2.50036E6

C(127) = 0.3336E6

C(126) = C(125)+C(127)

Soil roughness length; ZLND

Ocean roughness length; ZOCE

Snow roughness length; ZSNO

von Karman constant; VONKAR

ZLND = 0.01

ZOCE = 0.00024

ZSNO = 0.00024

VONKAR = 0.378

Drag coefficient for soil under canopy:

CSOILC = 4.E-4

BDPOINT: This subroutine defines the pointers that locate variables within the F array. The data structure is designed for incorporation in a large model with buffer structure involving disk transfers.

INITB: It provides constants initial fields to boundary subroutine.

BMARCH: It provides time dependent driving parameters to BNDRY subroutine.

RAING_J: This subroutine is used to allow for simulation of spatially inhomogeneous conditions in precipitation input.

SOLBDC: The subroutine writes many of the soil constants as a function of location (JLON, JILT). The soil parameters given in Table 3 are defined here.

ALBEDO: It calculates albedos over land (bare soil and vegetated), sea ice, open ocean and snow albedos (on bare ground and over vegetation with snow).

ZENITH: This subroutine is used by radiation package in CCM and can be called from albedo. However, it is not yet used here. It computes the zenith angle at each of 'IMAX' (number of equally spaced longitude values) at latitude 'ALAT', for a diurnally varying sun.

BNDRY: This is the main routine when interfacing with a meteorological model.

DRAG: It determines surface transfer coefficients at anemometer level from lowest model level based on Monin-Obukov theory using Deardorff parameterization in terms of bulk Richardson number. It calculates neutral drag coefficient (CDRN) as a function of underlying surface and modifies CDRN as a function of bulk Richardson number of surface layer.

DRAGDN: It returns neutral drag coefficient for grid square.

DEPTH: It calculated snow depth parameters, viz., fraction of vegetation covered by snow, fraction of vegetation cover, excluding snow-covered vegetation, fraction of soil covered by snow, snow depth, ratio of snow density to density of H_2O.

SATUR: The subroutine calculates saturation vapour pressure and saturated specific humidity (dimensionless).

VCOVER: It provides leaf and stem area parameters; depends on climate through subsoil temperatures.

DRIP: It puts excess leaf water into rain or snow and leaf water is reset to its maximum value.

LEFTEM: It calculates leaf temperature, leaf fluxes and net transpiration.

STOMAT: This subroutine gives leaf stomatal resistance from environmental parameters under conditions of no moisture stress.

FRAWAT: It determines fraction of foliage covered water FWET, and the fraction of the foliage that is dry transpiring leaf FDRY. Their definitions differ - FWET is the fraction of all vegetative surfaces which are wet because stems can evaporate, FDRY is the fraction of leaf area index which is dry because only leaves can transpire.

ROOT: This subroutine provides root function in terms of maximum transpiration rate that plants can sustain depending on soil moisture.

LFDRAG: It recalculates stability dependent drag coefficient for vegetation, given the natural drag coefficient.

CONDCH: The subroutine calculates dimensional and non-dimensional sensible heat conductances for canopy and soil flux.

CONDCQ: It computes dimensional and non-dimensional latent heat conductances for canopy and soil flux.

DERIV: It gives derivatives of energy fluxes with respect to leaf temperature for Newton-Raphson calculation of leaf temperature.

CO_2: This subroutine gives plant carbon uptake and dead carbon decomposition.

CARBON: It provides whole leaf photosynthesis.

TSEICE: This subroutine gives sensible and latent heat fluxes and snow melt over ice.

TGRUND: It calculates soil surface and sub-soil temperatures.

SNOW: It updates snow cover and snow age.

WATER: This updates soil moisture and runoff and calculates fluxes through air, surface layer and root layer faces.

BUFOUT: It moves output fields to output buffer.

OUTB: This subroutine provides output for off line boundary simulations.

4.2 Input Data Description

In order to run the model the following data are needed:

4.2.1 METEOROLOGICAL DATA

If BATS is coupled to the climate model the meteorological parameters are transferred from the climate model. However, for off line boundary simulations the following meteorological data need to be provided to the model:

1. Relative humidity, RHUM
2. Anemometer temperature (K)
3. Surface pressure (pa)
4. Anemometer westerly wind (m/s)
5. Anemometer southerly wind (m/s)
6. Precipitation (mm/s)

7. Diurnal temperature range factor (K)
8. Noontime maximum radiation received at surface (SI units)

4.2.2 SOIL DATA

Besides the soil parameters given in Table 3 and provided in the model through SOLBDC and ALBEDO the following parameters are also specified in the model:

1. Root zone soil water (mm)
2. Total soil water (mm)
3. Surface water (mm)

4.2.3 VEGETATION DATA

The vegetation data are provided in the model through BLOCK DATA. Besides these the following parameters are also provided:

1. Fractional vegetation cover
2. Vegetation cover (based on Table 2)
3. Carbon uptake (kg carbon/m**2/s)
4. Respiratory rate (kg C/m**2/s)

4.2.4 SNOW DATA

For surface types with snow the model needs the following data:

1. Snow cover (mm water equivalent)
2. Nondimensional snow age
3. Sea ice thickness (mm)

4.2.5 OTHER CONSTANTS

Besides the input data given in sections 4.2.1 to 4.2.4, the constants specified in subroutine BDCON are also required by the model.

4.3 Output Description

The model finally evaluates the following parameters at an interval of half an hour:

1. Temperature of air above canopy (K)
2. Foliage temperature (K)
3. Temperature of soil at surface (ground temperature) (K)

4. Temperature of subsoil (K)
5. Net absorbed solar radiation (W/m**2)
6. Instantaneous sensible heat (W/m**2)
7. Evaporation (W/m**2)
8. Water on foliage (mm)
9. Total soil water (mm)
10. Water in upper soil (mm)
11. Root zone soil water (mm)
12. Surface runoff (mm/day)
13. Total runoff (mm/day)
14. Precipitation (mm/s)
15. Anemometer westerly wind (m/s)
16. Anemometer southerly wind (m/s)
17. Bowen ratio
18. Respiration rate (kg C/m**2/s)

The output is written in subroutine OUTB.

5.0 SUBGRID SCALE VARIABILITY IN PRECIPITATION

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. It considers the same precipitation throughout the grid. BATS was modified at Colorado State University to allow the simulation of spatially inhomogeneous conditions in precipitation input (The subroutine used for accounting the variability in precipitation is RAING_). The precipitation intensity, the inter arrival time between precipitation pulses and the storm duration generated in the model are assumed to follow exponential distribution.

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

The precipitation generated in the model is spatially inhomogeneous. In a given time step one subgrid gets wet and the choice of the subgrid to get wet is random. The average of fields of different subgrids (average of spatially inhomogeneous distributed fields) are evaluated, considering spatially inhomogeneous precipitation input.

6.0 REMARKS

Biosphere Atmosphere Transfer Scheme (BATS) developed at NCAR is documented here. Model is basically developed for coupling it with CCM though off line studies are also performed. All the physical processes encountered in the model are explained in detail. Sequence of subroutines, their purposes, input and output details are also described. Document will prove of much help in running the BATS and also in developing increased understanding of atmosphere - land surface interactions and in order to assess the potential effects on global and regional hydrology. Subgrid scale variability in precipitation is also described.

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List of Mathematical Symbols

α_f	Albedo of the vegetative canopy
α_{IR}	Snow albedo for near-infrared radiation
α_{IRD}	Snow albedo for diffuse near-infrared radiation
α_{IR0}	= 0.65, albedo of new snow for near-infrared solar radiation with solar zenith angle less than 60°
α_V	Snow albedo for visible solar radiation
α_{VD}	Snow albedo for diffuse visible solar radiation
α_{V0}	= 0.95, albedo of new snow for visible solar radiation with solar zenith angle less than 60°
$\Delta\alpha_g$	Increase of albedo due to dryness of soil surface
Δt	Model time step
β	Fraction of transpiration from top soil layer
ε	Thermal emissivity of ground
κ	R/C_p
λ	Wavelength of radiation
λ_s	Thermal diffusivity coefficient
ρ_a	Density of surface air
ρ_i	Density of ice relative to water
ρ_s	Density of subsurface soil layer
ρ_{sw}	Density of snow relative to water
ρ_w	Volume of liquid water per unit volume of soil, weighted toward top layer as defined by Eq. (18a)
ρ_{wsat}	Porosity or saturated soil water density
σ	Ratio of pressure p to surface air pressure p_s
σ_f	Fractional foliage cover for each grid point
σ_s	Stefan–Boltzmann constant
τ_{SNOW}	Nondimensional age of snow

τ_0	Time constant used in calculation of age of snow
τ_1	Period of heating (in soil temperature calculation) = 8.64×10^4 seconds = 1 day
ϕ	Soil water suction (negative potential)
ϕ_{MAX}	Soil water suction for permanent wilting of plants
ϕ_0	Soil water suction for saturated soil
Υ_{ro}	Maximum transpiration that can be sustained
Υ_w	Rate of transfer of water by diffusion to the upper soil layer from the lower; subscript zero denotes rate in the absence of gravity
a	Fraction of sea ice covered by leads
c_i	= Specific heat of ice $\simeq 0.45\ c_w$
c_s	Specific heat of subsurface layer
c_{sw}	= $0.49\ c_w$, specific heat of snow for unit snow density
c_w	= 4.186×10^6 J m^{-3} K^{-1}, specific heat of water
$c_{A,F,V}$	Various bulk conductances as defined in the text
c_1	= $2\pi^{1/2} = 3.5449$ (in ground temperature calculation)
c_2	= 2π (in ground temperature calculation)
c_3	= rate of subsoil relaxation = 0.2 (in soil temperature calculation)
d_{ie}	Equivalent water depth of snow
d_{ice}	Depth of ice
d_s	= $10\ S_{cv}/\rho_{sw} = 10 \times$ snow depth
d_1	= $(k_s\tau_1)^{1/2}$ is soil depth influenced by periodic heating
f	Ratio of soil evaporation to potential evaporation
f_d	Fraction of vegetation that is green and unwetted
f_w	Fraction of wet foliage
f_{SNOW}	Fraction of grid square covered by snow
$f(ZEN)$	Increase of snow albedo due to solar zenith exceeding 60°

g	Acceleration due to gravity
h_s	$= (S_g + (F_{IR}^{\downarrow} - F_{IR}^{\uparrow}) - F_s - L_{v,s}F_q - L_f S_m)$, heat balance at the surface
k	von Karman constant
k_s	Soil or snow thermal conductivity
p_s	Surface air pressure
p_1	Lowest model level air pressure
q	Specific humidity
q_1	Lowest model level water–vapor mixing ratio
q_{af}	Water–vapor mixing ratio of the air within the foliage
q_g	Soil surface water–vapor mixing ratio
$q_{g,s}$	Saturated mixing ratio at soil surface temperature
q_s	Water–vapor mixing ratio inside the leaves
r_a	Aerodynamic resistance factor $(1/(C_f U_{af}))$
r_s	Stomatal resistance factor
$r_{\ell a}$	Resistance to heat or moisture transfer through the laminar boundary layer at the foliage surface
r_F	$= r_{\ell a}/(\sigma_f L_{SAI})$, bulk foliage resistance
r_v	Average resistance for transfer of water vapor from foliage due to stomatal and aerodynamic resistance of the foliage surface
r_1	Rate of "snow aging" due to grain growth from vapor diffusion
r_2	Rate of "snow aging" due to melt water
r_3	Rate of "snow aging" from dirt and soot
r''	Fraction of potential evaporation from a leaf
s	Volume of water in soil divided by volume of water at saturation
s_i	Soil water as defined above in layer i
s_w	Soil water as defined above at permanent wilting point

t	Time
u_1	Lowest model level west-to-east wind component
u^*	Friction velocity (ρu^{*2} = surface momentum flux)
v_1	Lowest model level south-to-north wind component
z_0	Roughness length
z_1	Height of lowest model level
A_{LBG}	Albedo for bare soil
A_{LBL}	Albedo of plants for infrared radiation
A_{LBS}	Albedo of plants for short-wave radiation
A_{LBGO}	Albedo for wet bare soil
B	Soil parameter defining change in soil water potential and hydraulic conductivity with soil water, a function of soil texture
C_f	Coefficient of transfer between foliage and air in the foliage
C_p	Specific heat of air
C_s	Constant in snow albedo calculation (= 0.2)
C_D	Surface drag coefficient
$C_{D,F}$	Average momentum transfer coefficient over the grid square in the presence of vegetation
C_{DH}	Aerodynamic transfer coefficient for heat
C_{DN}	Drag coefficient for neutral stability
C_{DVEG}	Aerodynamic drag coefficient for the canopy
C_{DW}	Aerodynamic transfer coefficient for water vapor
C_N, C_S	Constants in snow albedo calculation (= 0.5, 0.2)
$C(ZEN)$	Cosine of the solar zenith angle
D	Average diffusivity for water flow through soil
D_f	Characteristic dimension of foliage elements in direction of wind flow
D_s	Rate of excess snow dropping from leaves per unit land

D_w	Rate of excess water dripping from leaves per unit land area
D_{min}	Minimum value of soil diffusivity
D_{max}	$= B\phi K/\rho_{wm}$, maximum value of soil diffusivity
$E_{a,f,g}$	Water flux per unit land area; f refers to origin at foliage, g at ground, and a to the total flux; a superscript N, in Eq. (70)-(71), refers to the flux at the Nth iteration for leaf temperature
E_{tr}	Transpiration
E_{trmx}	Maximum transpiration the vegetation can sustain
E_D	Evaporation demand as determined by the air-ground humidity difference
F_c	Heat conduction through snow-covered sea ice or bare sea ice
F_s	Atmospheric sensible heat flux from ground to atmosphere
F_q	Moisture flux from ground to atmosphere
F_{qm}	Moisture flux through the wet surface that the soil can sustain, *i.e.*, maximum as limited by diffusion
F_{vi}	Visible radiation incident at the top of the canopy
F_{vl}	Visible radiation absorbed by the lower canopy
F_{vu}	Visible radiation absorbed by the upper canopy
F_{AGE}	Snow age factor
$F_{IR}^{\downarrow}$ - $F_{IR}^{\uparrow}$	Net long-wave radiation flux from atmosphere to bare ground
$F_{SEAS}(T)$	Seasonal variation of vegetation cover with temperature (Eq. 1b)
G	Net water applied to the surface $(P_r + S_m - F_q)$ in absence of vegetation
G_{HEAT}	Heat conduction rate from surface to underlying reservoir
$H_{a,f,g}$	Heat flux per unit land area to the atmosphere; f refers to origin at foliage, g at ground, a to total flux

K	Hydraulic conductivity of soil
K_0	Saturated soil hydraulic conductivity, equivalent to downward flow rate for saturated soil due to gravity
K_{VEG}	Land use/vegetation type in model
L_d	Unwetted fraction of leaf-stem area free to transpire
L_f	Latent heat of fusion
L_s	Latent heat of sublimation
L_v	Latent heat of evaporation
$L_{v,s}$	Either L_v or L_s, depending on whether T_g is greater than freezing or not
L_w	Ratio of wetted leaf stem area to total leaf stem area exchanging water with the atmosphere
L_{AI}	Leaf area index
L_{SAI}	Leaf-stem area index, sum of L_{AI} and S_{AI}
L_{SAIW}	Total vegetation surface that exchanges water with the atmosphere
P	Precipitation rate
P_r	Rate of precipitation falling as rain
P_s	Rate of precipitation falling as snow
Q_c	Latent heat release
R	Gas constant
R_f	Dependence of the stomatal resistance factor on solar radiation
R_g	Leakage down to subsoil and groundwater reservoirs
Ri_B	Surface bulk Richardson number
R_m	Net radiation that would be absorbed by the vegetation if the foliage temperature $= T_{g1}$
R_n	Net radiation absorbed by the vegetation
R_s	Surface runoff

R_{ti}	Fraction of roots in the soil layer
R_w	Total runoff ($R_s + R_g$)
R_{OUGH}	Assigned roughness of vegetation types in model
$S^{\downarrow}$	Incident solar flux
S_f	Dependence of the stomatal resistance factor on temperature
S_g	Solar radiation absorbed over bare ground at earth's surface
S_m	Rate of snow melt
S_{cv}	Snow cover (liquid water equivalent)
S_{cv}/ρ_{sw}	Average snow depth
S_{gf}	Solar flux absorbed by vegetation
S_{sw}	Surface soil water in upper layer of soil in meters (maximum value = S_{swmax})
S_{tw}	Total water in rooting zone of soil (maximum value = S_{twmax})
S_{AI}.	Stem area index
S_0	S_{tw}/S_{twmax}
S_1	S_{sw}/S_{swmax}
T_a	Air temperature at 10 m over ocean, 1.3 m over grass for land
T_{af}	Temperature within the foliage layer
T_c	Reference temperature for deciding whether precipitation is rain or snow
T_f	Temperature of foliage
T_{g1}	Surface soil temperature
T_{g2}	Subsurface temperature (depth of about 0.2 m)
T_{g3}	Deep soil temperature (depth of about 2 m = annual average)
T_m	= 273.16 K, the melting or freezing temperature of pure water
T_B	Approximate freezing point of sea water
T_1	Air temperature of lowest model layer $\times(p_1/p_s)^{-\kappa}$
U_{af}	Magnitude of wind within the foliage layer
U_c	Subgrid-scale horizontal convection velocity

V_a	$= (u_1^2 + v_1^2 + U_c^2)^{1/2}$, strength of wind at the anemometer level
W_{dew}	Total water stored by canopy per unit land area
W_{DMAX}	Maximum water the canopy can hold
W_{LT}	Soil dryness (or plant wilting) factor
W_{m1}	Rate of melting (freezing if negative) of surface soil water
W_{m2}	Rate of melting (freezing if negative) of subsurface soil water
Z_0	Depth of total active soil layer, varies typically from 0.5 to 2 m in thickness as a function of vegetation cover and/or land use
	Depth of upper soil layer, fixed at 0.10 up to now

DIRECTOR	S M SETH
SCIENTISTS	R MEHROTRA
	DIVYA