JAEA-Data/Code
2008-033

JAEA-Data/Code

Improvement of a Land Surface Model for Accurate Prediction of Surface Energy and Water Balances

Genki KATATA

Research Group for Environmental Science
Nuclear Science and Engineering Directorate

February 2009

Japan Atomic Energy Agency | 日本原子力研究開発機構

独立行政法人日本原子力研究開発機構　研究技術情報部　研究技術情報課
〒319-1195　茨城県那珂郡東海村白方白根 2 番地 4
電話 029-282-6387, Fax 029-282-5920, E-mail:ird-support@jaea.go.jp

JAEA-Data/Code 2008-033

Improvement of a Land Surface Model for Accurate Prediction of Surface Energy and Water Balances

Genki KATATA

Division of Environment and Radiation Sciences
Nuclear Science and Engineering Directorate
Japan Atomic Energy Agency
Tokai-mura, Naka-gun, Ibaraki-ken

(Received December 19, 2008)

In order to predict energy and water balances between the biosphere and atmosphere accurately, sophisticated schemes to calculate evaporation and adsorption processes in the soil and cloud (fog) water deposition on vegetation were implemented in the one-dimensional atmosphere-soil-vegetation model including CO2 exchange process (SOLVEG2). Performance tests in arid areas showed that the above schemes have a significant effect on surface energy and water balances. The framework of the above schemes incorporated in the SOLVEG2 and instruction for running the model are documented. With further modifications of the model to implement the carbon exchanges between the vegetation and soil, deposition processes of materials on the land surface, vegetation stress-growth-dynamics etc., the model is suited to evaluate an effect of environmental loads to ecosystems by atmospheric pollutants and radioactive substances under climate changes such as global warming and drought.

Keywords: Land Surface Model, Atmosphere, Soil, Vegetation, Cloud Water Deposition, Evaporation, Adsorption

JAEA-Data/Code 2008-033

地表面エネルギー・水収支の高精度な予測のための地表面モデルの高度化

日本原子力研究開発機構　原子力基礎工学研究部門　環境・放射線工学ユニット
堅田　元喜

（2008 年 12 月 19 日　受理）

大気－陸面間の熱・水交換過程を高精度に評価するために、土壌中の蒸発・吸着過程や植生への雲（霧）水沈着過程などの新しいスキームを、CO_2交換過程を含む大気－土壌－植生 1 次元モデル(SOLVEG2)に導入した。著者は、これまでの研究でこのモデルを乾燥地域に適用し、これらの物理過程が地表面エネルギー・水収支に重要な影響を与えることを示した。本報告では、大気・土壌・植生サブモデルのそれぞれ導入された新しい物理スキームに関する物理方程式、および改良したモデルの利用方法について、詳細に記述した。今後、開発したモデルに土壌－植生間の炭素交換、大気から陸面への物質沈着、植物のストレス・生長・動態などを組み込むことによって、地球温暖化や干ばつなどの気候変動の影響を含めた放射性物質等の環境負荷物質による生態系への影響を評価・予測することが可能となる。

原子力科学研究所（駐在）：〒319-1195　茨城県那珂郡東海村白方白根 2-4

Contents

目　次

1. Introduction

The energy and water exchanges between the atmosphere and land surface are important for environmental studies such as the prediction of climate change, but are not well understood. Especially, it is a challenging study to model and clarify these exchanges among the atmosphere, soil, and vegetation under climate changes (such as global warming) and human activities. In addition, the processes of heat and water exchanges at the air-land surface strongly affect the material exchange of air pollutions, plant nutrients, radionuclide substances, etc. to the land surface. Therefore, it is necessary to develop a detailed land surface model which is applicable to various environmental issues.

A detailed one-dimensional model for atmosphere-soil-vegetation interaction called SOLVEG2 has been developed (Nagai 2004) [1)]. The SOLVEG2 is unique in the way it treats phase change process between liquid and water vapor in the soil and turbulent transfer of cloud liquid water in the atmosphere (fog), momentum, heat, and water vapor. The new schemes of phase change processes in the soil and cloud water deposition on vegetation have been lately developed (Katata et al. 2007 [2)] and 2008 [3)]). These schemes are especially suitable for accurate prediction of surface energy and water balances. For example, dew deposition and vapor adsorption have been shown by Agam (Ninari) and Belriner (2006) [4)] to be the most important water source in desert areas during the dry season. Furthermore, dew at the soil surface has been shown to be an important source of moisture for plants, biological soil crusts, insects, and small animals in desert areas (Jacobs et al., 1999) [5)]. Moreover, latent heat fluxes due to dew and adsorption significantly affect the energy balance at the soil surface (Agam (Ninari) et al. 2004) [6)]. For woody plants, fog deposition has long been recognized to be as an important factor in determining water balance of mountainous vegetation, especially in arid and semi-arid regions. Fog occurring in the surface boundary layer is transported downward by turbulence generated by strong wind shears at terrestrial surfaces such as plant canopies, and is captured by them. If the cloud water captured on foliar and woody surfaces of plants does not exceed the storage capacity of the canopy during fog deposition, the water is either lost from the canopy to the atmosphere via surface evaporation, or it is directly absorbed by the leaves (Burgess and Dawson 2004) [7)]. If the intercepted water increases above the storage capacity, the water on the plant surface drips to the soil via throughfall and stemflow. This phenomenon is known as fog precipitation (Hutley et al. 1997) [8)]. Fog precipitation can be considered to be a crucial water resource and should be quantified for accurate prediction of water budget in arid areas. Considering the difficulty in collecting accurate meteorological or hydrological data in arid environments on an annual or interannual basis, it is necessary to develop a novel land surface model which is applicable to the arid environment for better predictions of surface energy and water balances underlying material exchanges between the atmosphere and biosphere.

The objective of this study is to summarize the framework of the new schemes incorporated in the original SOLVEG2. Future prospects for an application of the modified SOLVEG2 to environmental issues are also described in the paper.

2. Model overview

The SOLVEG2 model consists of one-dimensional multilayer sub-models for atmosphere, soil, and vegetation with a radiation transfer scheme for calculating the transmission of solar and long-wave radiation fluxes in the canopy layer. The variables from the bottom of soil layer to the top of air layer were integrated numerically using an implicit finite difference method and Gaussian elimination method. A detailed description of SOLVEG2 can be found in Nagai (2004) [1]. In the present study, the soil, atmosphere and vegetation components of SOLVEG2 were modified to model the processes of evaporation and adsorption in the soil and cloud water deposition on vegetation more precisely. Basic equations for sub-models and the newly incorporated processes are described here. Details of modifications and model performance tests are described in Katata et al. (2007) [2] and (2008) [3].

3. Modifications of soil sub-model

3.1. Basic equations

The temporal change in soil temperature is expressed by the heat conduction equation as

$$C_s \rho_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T_s}{\partial z} \right) - lE_b , \tag{3-1}$$

where t is the time [sec], z the depth of the soil [m], T_s the soil temperature [K], C_s and ρ_s the specific heat [J kg^{-1} K^{-1}] and the density of the bulk soil [kg m^{-3}], respectively, λ the thermal conductivity [Wm^{-1}K^{-1}], l the latent heat of vaporization [J kg^{-1}], and E_b the phase changes of soil water [kg m^{-2} s^{-1}], respectively.

The mass balance equation for liquid water is given as

$$\rho_w \frac{\partial \eta_w}{\partial t} = \frac{\partial}{\partial z}\left(D_w \frac{\partial \eta_w}{\partial z} + K \right) - E_b , \tag{3-2}$$

where η_w is the volumetric soil water content [m^3 m^{-3}], D_w is the soil water diffusivity [m^2 s^{-1}], K the unsaturated hydraulic conductivity [m s^{-1}], and ρ_w the density of liquid water [kg m^{-3}]. The soil water diffusivity D_w is expressed by

$$D_w = K \frac{\partial \psi}{\partial \eta_w} , \tag{3-3}$$

where ψ is the water potential [m].

Water vapor diffusion in the soil is considered in SOLVEG2. According to Fick's law, the diffusion equation of water vapor in the soil pores is expressed as

$$\rho \frac{\partial (\eta_{ws} - \eta_w) q_s}{\partial t} = \frac{\partial}{\partial z} \rho \varepsilon_t \left(D_v (\eta_{ws} - \eta_w) \frac{\partial q_s}{\partial z} \right) + E_b , \tag{3-4}$$

where q_s is the specific humidity in the soil pores [kg kg^{-1}], D_v the diffusion coefficient of water vapor [m^2 s^{-1}], ε_t the tortuosity, ρ the density of water vapor [kg m^{-3}] and η_{ws} the saturated volumetric water content [m^3 m^{-3}]. The variable ($\eta_{ws} - \eta_w$) represents the volumetric content of gaseous phase in the soil. The ε_t was chosen as two-thirds, as recommended by Jackson et al. (1974) [9]. Convection of water vapor is neglected in SOLVEG2 because its contribution to water vapor transport near the soil surface is small under the natural condition that moderate heating and cooling processes are caused by diurnal change of solar radiation (Grifoll et al. 2005) [10]. Although empirical relations for water vapor enhancement factor have been proposed to match measurements with predictions of Philip and DeVries (1957) [11] model, such modifications have not yielded satisfactory agreement with field data (Cahill and Parlange 1998) [12]. SOLVEG2 simulates water vapor movement in the soil without introducing such empirical relations.

3.2. Soil thermal characteristics

The following formulae of λ and $C_s\rho_s$ are used in the original SOLVEG2

$$\lambda = \begin{cases} \max[1.0, 419\exp(-pF-2.7)] & (pF \le 5.1) \\ 0.172 & (pF > 5.1) \end{cases}, \quad (3\text{-}5)$$

$$C_s\rho_s = (C_s\rho_s)_{soil} + \eta_w (C_s\rho_s)_{water}, \quad (3\text{-}6)$$

where $pF=\log_{10}(-\psi)+2$. Although the above functions suggested by McCumber and Pielke (1981) [13] has been used in numerous land surface models, it is known that Eq. (3-5) tends to overestimate (underestimate) λ which affects surface energy fluxes during wet (dry) periods (Peters-Lidard et al. 1998) [14]. Thus, in the modified version, Eq. (3-5) is replaced by the more precise formulation of λ by McInnes (1981) [15]

$$\lambda = A + B\eta_w - (A-D)\exp\left[-(C\eta_w)^E\right], \quad (3\text{-}7)$$

where A, B, C, D, and E are constants derived from De Vries (1963) [16] given as

$$\begin{aligned} A &= 0.65 - 0.78\rho_d + 0.6\rho_d^2, \\ B &= 1.06\rho_d, \\ C &= 1.0 + 2.6(m_c/100)^{-0.5}, \\ D &= 0.03 + 0.1\rho_d^2, \\ E &= 4.0, \end{aligned} \quad (3\text{-}8)$$

where ρ_d is the dry bulk density of the soil [kg m^{-3}], and m_c the clay fraction [%]. Since the ρ_d for most soils ranges between 1.1 and 1.6 kg m^{-3}, the value of 1.45 kg m^{-3} for sandy loam (Agam (Ninari) and Berliner 2004) [6] is applied to all soils. The formulation of $C_s\rho_s$ validated in Katata et al. (2007) [2] is also replaced as the following formulation by Brutsaert (1982) [17]

$$C_s\rho_s = (1.095 + 4.18\eta_w)\times 10^6. \quad (3\text{-}9)$$

Sample calculations of λ and $C_s\rho_s$ using Eq. (3-5) and (3-6) together with Eq. (3-7) and (3-8) for a volcanic soil in Spain ('Other' soil in Table 3-1) is shown in Fig.3-1.

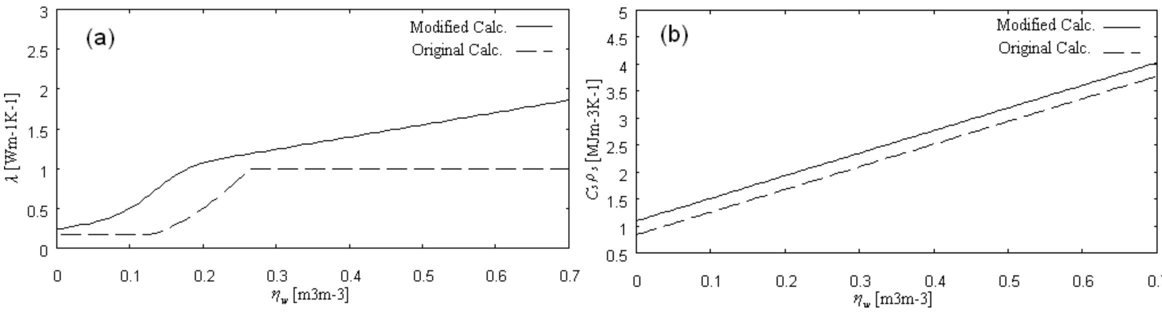

Fig.3-1 Comparisons of (a) soil thermal conductivity and (b) volumetric heat capacity between original (red lines) and modified formulations (green lines).

3.3. Soil water characteristics

The soil water retention curve is essential for the simulation of liquid and water vapor flow in an unsaturated zone. The original SOLVEG2 uses the commonly employed curve suggested by Brooks and Corey (1964) [18] and expressed as

$$\psi = \psi_s \left(\frac{\eta_w}{\eta_{ws}} \right)^{-b}, \tag{3-10}$$

and $$K = K_s \left(\frac{\eta_w}{\eta_{ws}} \right)^{2b+3}, \tag{3-11}$$

where ψ_s and K_s are the saturated values of water potential [m] and K [m s^{-1}], respectively, and b is the empirical constant. These equations are widely used in various land surface models because of their simplicity. The function of (3-10) has, however, significant limitations at low soil water content. Since the Brooks and Corey's curve has been designed for wet soil, it is generally used to predict ψ when η_w is larger than the wilting point. The curve, hence, cannot be applied to dry soil. Moreover, water vapor adsorption is controlled by water retention curves in dry soil. The direct use of the curve for dry soil leads to errors not only in the prediction of the actual soil water content but also in the evaluation of adsorption processes in dry soil. A more applicable curve for dry soil is therefore needed.

To avoid this problem, the authoer adopted a modified soil water retention curve suggested by Webb (2000) [19] consisting of two regions: the capillary region (van Genuchten 1980) [20] and the adsorption region (Campbell and Shiozawa 1992) [21]. The functions of both curves are described by Webb (2000) [19] as

$$\psi = \begin{cases} \alpha^{-1}\left(S_w^{-(1/m)} - 1\right)^{(1/n)} & (\eta_w \geq \eta_{wm}) \\ 10^{[\gamma(S - S_{wm}) + \log_{10}\psi_m]} & (\eta_w < \eta_{wm}) \end{cases}, S_w = (S - S_r)/(1 - S_r),, \tag{3-12}$$

where S, S_r, S_w, and S_{wm} are the saturation ratio, residual and effective saturation ratio, and the corresponding value of S_w when $\eta_w = \eta_{wm}$, respectively, and α, n, and m (= 1－1/n) are fitting parameters, and ψ_m water potential when $\eta_w = \eta_{wm}$ [m]. The K can be described by combining Mualem's pore-size distribution model (Mualem 1976) [22]

$$. \ K = K_s S_w^2 \left[1 - \left(1 - S_w^{1/m}\right)^m\right]. \tag{3-13}$$

As an example, modified soil water retention curve and unsaturated hydraulic conductivity using Eq. (3-12) and (3-13) together with Eq. (3-10) and (3-11) for a volcanic soil in Spain ('Other' soil in Table 3-1) are shown in Fig.3-2. As seen in the Fig.3-2 (a), the values of ψ calculated by Eq. (3-10) approach infinity with decreasing amounts of water in the dry soil. In contrast, the modified curves can be applied to the regions from water saturation to extreme drying. The summary of parameters for Eq. (3-12) and (3-13) is listed in Table 3-1.

(a) (b)

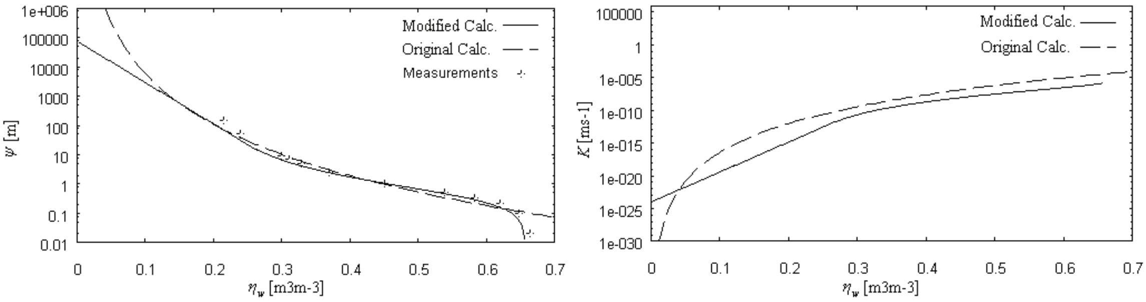

Fig.3-2 Comparisons of (a) soil water retention curves and (b) unsaturated hydraulic conductivity between original (red lines) and modified formulations (green lines).

Table 3-1 List of parameters for modified soil sub-model (from Carsel and Parrish 1988) [23].

	Soil type	η_w (m^3m^{-3})	α^{-1} (m^{-1})	κ	n	η_{wr} (m^3m^{-3})	m_c (%)	K_s (ms^{-1})
1	Sand	0.430	0.069	1.70×10^{3}	2.68	0.045	2.90	8.25×10^{-5}
2	Loamy sand	0.410	0.081	2.15×10^{3}	2.28	0.057	6.40	4.05×10^{-5}
3	Sandy loam	0.410	0.133	1.42×10^{3}	1.89	0.065	11.1	1.23×10^{-5}
4	Silt loam	0.450	0.500	1.15×10^{2}	1.41	0.067	18.5	1.25×10^{-6}
5	Silt	0.460	0.625	3.00×10^{1}	1.37	0.034	9.50	6.94×10^{-7}
6	Loam	0.430	0.278	5.20×10^{2}	1.56	0.078	19.7	2.89×10^{-6}
7	Sandy clay loam	0.390	0.169	1.00×10^{3}	1.48	0.100	27.4	3.64×10^{-6}
8	Silty clay loam	0.430	1.000	1.65×10^{1}	1.23	0.089	33.2	1.94×10^{-7}
9	Clay loam	0.410	0.526	9.80×10^{1}	1.31	0.095	32.6	7.22×10^{-7}
10	Sandy clay	0.380	0.370	6.00×10^{1}	1.23	0.100	41.0	3.33×10^{-7}
11	Silty clay	0.549	0.374	2.00×10^{1}	1.19	0.000	46.8	5.56×10^{-9}

12	Clay	0.446	6.667	3.50×10^{0}	1.17	0.000	65.0	9.49×10^{-9}
13	Organic	0.430	0.278	5.35×10^{2}	1.56	0.078	19.7	2.89×10^{-6}
14	Water	1.000	0.000	0.00×10^{0}	0.00	0.000	0.00	0.00×10^{0}
15	Bedrock	0.250	1.234	3.68×10^{2}	1.04	0.150	5.00	1.25×10^{-5}
16	Other	0.666	0.377	1.90×10^{2}	1.50	0.198	19.7	4.00×10^{-5}

3.4. Phase change processes of soil water

The explicit calculation of phase change processes (evaporation, condensation and adsorption) in the soil (E_b) incorporated in the original SOLVEG2 are described by (3-1), (3-2), and (3-4). The formulation of E_b is expressed as

$$E_b = \rho r_b^{-1}\left[q_{sat}(T_s) - q_s\right] \tag{3-14}$$

where r_b is the function of volumetric soil water content empirically determined by Kondo et al. (1992) [24] as

$$r_b = 0.02F_1(\eta_{ws} - \eta_w)^{F_2} D_v^{-1} \tag{3-15}$$

where F_1 and F_2 are the constants. The above formulations have, however, no theoretical background which can be used to phase change processes in the soil. Thus, a new formulation for E_b is proposed and introduced to the modified SOLVEG2.

In the modified SOLVEG2, the soil is formed by aggregation of "cylindrical pores" each of which has a different radius as shown in Fig.3-3a. We assume that only two patterns of pores exist. One is filled with capillary water, and the other is filled with air and adsorbs water on its wall. The drying mechanism of the soil in the modified SOLVEG2 is illustrated by Fig.3-3b. When the soil is almost saturated, evaporation occurs at soil pores exposed to the air at the ground surface (direct evaporation, E_{dir} defined later in (3-30)). In this case, evaporation does not occur in the soil since almost all the pores are filled with capillary water (Fig.3-3b, 1). When the soil dries out, pores with a large radius are dehydrated and adsorb water films on their walls. As a result, evaporation of water adsorbed by large pores (evaporation in the soil, E_b) contributes to the water vapor flux in addition to evaporation from small water-filled pores at the ground surface (Fig.3-3b, 2). When the soil is extremely dry, all pores except for micro-pores are dehydrated and evaporation mainly occurs in the soil instead of at the ground surface (Fig.3-3b, 3). In modified SOLVEG2, water vapor flux at the air-land interface (i.e., total evaporation at the soil surface; z = 0) represents the sum of direct evaporation (E_{dir}) and water vapor flux from the pores with adsorbed water film to the atmosphere (E_0 defined later in (3-34)), which is resulted in evaporation in the soil throughout all soil layers. Similar models on the basis of cylindrical capillaries have been widely used to describe hydraulic and thermodynamic characteristics in unsaturated porous media (e.g., Mualem 1976) [22]. In the present study, we apply this concept to describe the phase change processes in the soil.

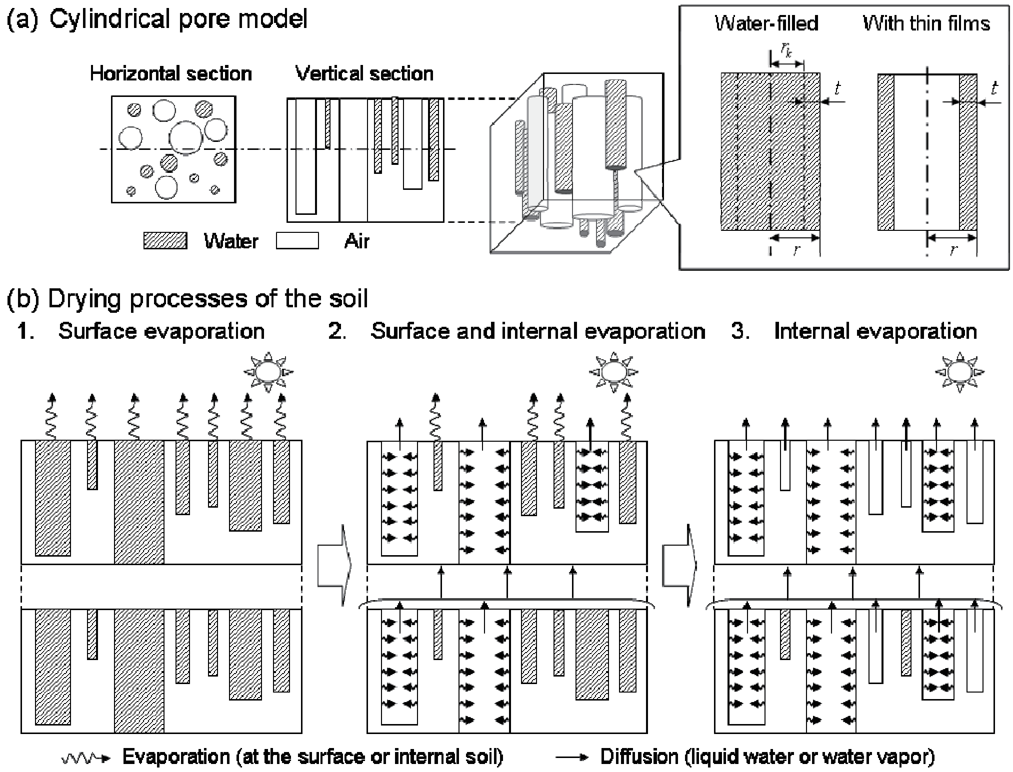

Fig.3-3 Schematic diagrams of (a) the cylindrical pore model and (b) the drying process of soil due to evaporation at the ground surface or in the soil

Considering the two patterns of pores (Fig.3-3a), a threshold radius of pores, r_k [m], which determines whether a pore is filled with capillary water or not, is expressed as

$$r_k = \frac{2\tau\cos\phi}{\rho_w g \psi} \tag{3-16}$$

where τ is the surface tension of the liquid water (= 0.072) [N m^{-2}], φ the contact angle of water (= 0) [degree], and g the gravity acceleration [m s^{-2}]. The largest pore radius in the filled pores, r [m], is calculated by $r = r_k + t$, where t is the film thickness of liquid water adsorbed on walls. t is given by (Derjaguin et al. 1978 [25]; Iwamatsu and Horii 1996 [26])

$$t = \sqrt[3]{\frac{A_{svl}}{6\pi\rho_w g\Pi}} \tag{3-17}$$

where A_{svl} is the Hamaker constant [J] for solid-vapor interactions through an intervening liquid (for condensation $A_{svl} < 0$) and Π the disjoining pressure [m]. Or and Tuller (1999) [27] determined $A_{svl} = -6.0\times10^{-20}$ [J] using soil data from Campbell and Shiozawa (1992) [21]. If interfacial interaction between the adsorbed water and the pore's wall surface is only induced by van der Waals forces, we can assume that the disjoining pressure Π is replaced by the water potential ψ (Tuller et al., 1999) [28]. It is assumed that only liquid film exists in the pores whose radius is larger than r_k. Using the soil water retention curve and the above formulations, we obtain the pore-size distribution of the soil. The cylindrical pore model detailed above has often been used to estimate pore size distribution of absorbents, e.g., activated carbon and silica gel.

The liquid-vapor interfacial area in the soil (A_{ia} [m^2 m^{-3}]) is simultaneously calculated with the discrete pore-size distribution, and is described as

$$A_{ia}(r) = 2\pi\kappa(r-t)L(r) \qquad \left(\sum_{r_{\min}}^{r} A_{ia}(r) \le SA\right) \tag{3-18}$$

where κ is the fitting parameter, $L(r)$ the pore length with r per unit volume [m m^{-3}], r_{min} the minimum radius in all of pores [m], and SA the specific surface area [m^2 m^{-3}]. The κ is determined from the fact that cumulative A_{ia} does not exceed measured SA. The values of κ for various soil textures are given in Table 3-1. From data from several soils (Petersen et al. 1996 [29]; Campbell and Shiozawa 1992 [21]; Banin and Amiel 1970 [30]), we obtained the following equation for SA

$$SA = \left(0.06m_c^2 + 2.01m_c + 5.0\right)\times10^3, \tag{3-19}$$

where m_c the clay content [%]. The following function of log-normal pore radius distribution, $f(r) = d\eta_w / dr$, is used in this study (Kosugi 1994) [31]

$$f(r) = \frac{\eta_{ws}}{(2\pi)^{1/2}\omega r}\exp\left[-\frac{\left[\ln(r/r_m)\right]^2}{2\omega^2}\right] \tag{3-20}$$

where r_m is the geometric mean radius [m], which is determined by ψ_{rm} [m] by (3-16), and ω standard deviation [m]. ψ_{rm} and ω are obtained from van Genuchten's parameters of α and m

$$\psi_{rm} = -\alpha^{-1}\left(2^{1/m}-1\right)^{1-m}, \tag{3-21}$$

and $$\omega^2 = (1-m)\ln\left[\left(2^{1/m}-1\right)/m\right], \tag{3-22}$$

Kosugi (1994) [31] has reported that this model performs as well as any existing empirical model for determining retention curves of various soils. Using (3-20), $L(r)$ is expressed from the surface area of a cylindrical pore

$$L(r) = \frac{f(r)}{\pi r^2} \approx \frac{f(r)\Delta r}{\pi r^2}, \tag{3-23}$$

Discrete calculation of $f(r)$ and $L(r)$ in the regions divided into four hundred from water saturation to extreme drying is carried out at each pore radius.

Assuming that the distribution of the relative humidity of air adjacent to adsorbed water is similar in all pores, when the relative humidity of air adjacent to adsorbed water is smaller than 35 %, almost all pores are filled with air and adsorb water according to the Brunauer-Emmett-Teller (BET) theory (Brunauer et al. 1938) [32]. Thus, we use the value of κ when the adsorbed water content, η_{wads}, is almost equal to η_w. η_{wads} is described as

$$\eta_{wads} = \eta_w \frac{\sum_{r\,\min}^{r} A_{ia}(r)}{SA}. \tag{3-24}$$

The capillary water content, η_{wmat}, is also determined as η_{wmat} ($=\eta_w - \eta_{wads}$). The changes of η_{wads} and η_{wmat} with ψ are shown in Fig.3-4a.

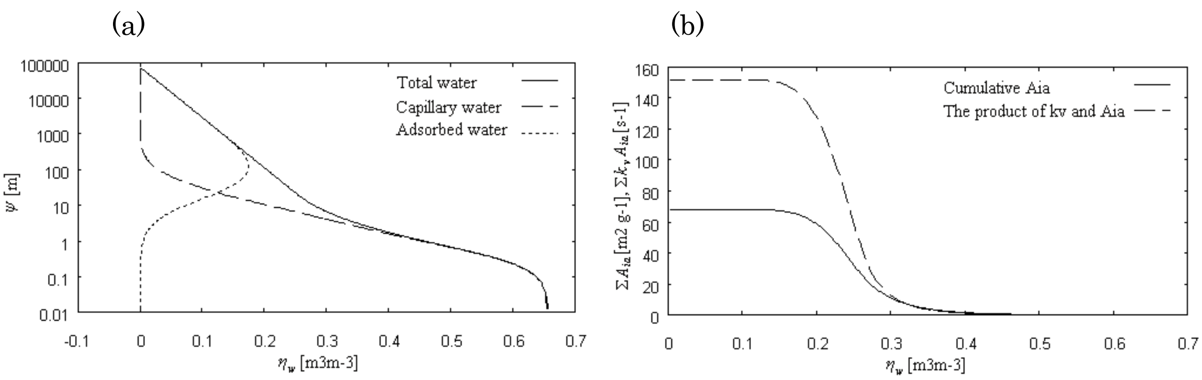

Fig.3-4 Samples of calculated (a) adsorbed (blue line), capillary (green line), and total soil water contents (red line), and (b) the cumulative air-water interfacial area in the soil (red line) and the product of mass transfer coefficient (k_v) and liquid-vapor interfacial area (A_{ia}) (green line).

To describe evaporation process in the soil, mass transfer model in the cylindrical tube (Bird et al. 2001) [33] was applied to the modified SOLVEG2. Since we assumed that specific humidity of air adjacent to adsorbed water is equally distributed in all pores, the evaporation rate of adsorbed water in a pore with r, $E_b(r)$, is determined by

$$E_b = \rho k_v(r) A_{ia}(r)(q_{wall} - q_s), \tag{3-25}$$

where $k_v(r)$ is the mass transfer coefficient [m s^{-1}] for a pore with r, q_{wall}, and q_s the specific humidity at the surface of water adsorbed on the wall and at the center of the cylindrical pore, respectively. k_v is calculated as follows

$$k_v = \frac{1.83 D_v}{r - t}, \tag{3-26}$$

where a value of 1.83 represents the Sherwood number of developed laminar flow of a circular tube. It can be assumed that gaseous phase in the soil is quiescent or laminar if any flow exists under small difference in pressure between the atmosphere and the soil (Rolsten 1986) [34], and liquid-vapor interfaces remains stable (Ranshoff and Radke 1988 [35]; Blunt and Scher 1995 [36]). Under such condition, mass transfer coefficient between the pore wall and bulk phase is constant (i.e., Sherwood number = 3.66) in the cylindrical tube regardless of bulk flow velocity if any; in other words, mass transfer coefficient is proportional to inverse r. Thus, if pore size distribution in the soil is given, the modified SOLVEG2 can provide the amount of evaporation in the soil, which is an integrated value of $E_b(r)$ throughout all pore radiuses. This is a new approach to describe detailed movements of liquid and water vapor including phase change processes in the soil.

In the modified SOLVEG2, evaporation occurs in pores not filled with capillary water whose radius is larger than r_k as calculated by (3-16). Therefore, the total evaporation rate in the soil at a certain η_w is represented by

$$(k_v A_{ia})_{tot} = \int_{r_{\min}}^{r_{\max}} k_v(r) A_{ia}(r) dr \approx \sum_{r_{\min}}^{r_{\max}} k_v(r) A_{ia}(r) \Delta r \,, \tag{3-27}$$

where r_{max} is the maximum radius in all of the pores [m]. The change of cumulative A_{ia} and $(k_v\ A_{ia})_{tot}$ for η_w are shown in Fig.3-4b. Result reveals the general concept of decreasing $(k_v\ A_{ia})_{tot}$ with an increase in soil water. This indicates that an increase of interfacial areas with a decrease in pores filled with capillary water allows more evaporation conductance of soil water; in other words, a thermodynamic equilibrium is formed between water vapor and liquid water when the soil dries out.

The q_{wall} is assumed to be equal to the specific humidity of air at the surface of liquid water adsorbed in the pores. When the soil water is in thermodynamic equilibrium, the relative humidity of the air adjacent to the adsorbed water in the pores, h_{ae}, is defined as (Israelachvili 1992) [37]

$$h_{ae} = \exp\left(\frac{\psi g}{R_w T_s}\right), \tag{3-28}$$

where R_w is the gas constant of water vapor [J mol^{-1} K^{-1}]. q_{wall} is thus expressed as

$$q_{wall} = h_{ae} q_{sat}(T_s), \tag{3-29}$$

Equation (3-28), combined with Eq. (3-16) forms the Kelvin equation, which is widely used to calculate the vapor pressure in thermodynamic equilibrium within a Representative Elementary Volume (REV). It also provides the relation of capillary radius (r) and saturated vapor pressure (q_{wall}) on spherical meniscus of the same curvature radius. Here, Kelvin's law is assumed to express vapor pressure of adsorbate on the cylindrical pore wall since it can be considered that vapor pressure of the water film adsorbed on the cylindrical pore wall with the same curvature radius, where van der Waals force works, is in the same order as that on the spherical meniscus. In the modified SOLVEG2, the soil water potential expressed by Eq. (3-12) which includes these effects is used to calculate ψ in (3-28) instead of (3-16).

Vapor diffusion with coefficient $(k_v\ A_{ia})_{tot}$ in (3-27) between the surface of adsorbed water and the air at the center of the cylindrical pore (evaporation or condensation in the soil) is caused by $(q_{wall}-q_s)$. The q_{wall} calculated by (3-29) rapidly decreases with decreasing soil water. When q_{wall} finally becomes q_s, evaporation (or condensation) in the soil by (3-25) stop.

We use the following equation for direct evaporation at the ground surface from the pores filled with capillary water, E_{dir}, which is regarded as evaporation

$$E_{dir} = \rho\sigma c_{E0}|\mathbf{u}|[q_{sat}(T_{s0}) - q_r], \qquad (3\text{-}30)$$

where σ is the fractional area of pores filled with capillary water exposed to the air ($\approx \eta_{wmat} / \eta_{ws}$), c_{E0} the bulk coefficient, $\boldsymbol{u}$ the horizontal wind speed, T_{s0} the soil surface temperature [℃], and q_r the specific humidity of the air [kg kg^{-1}]. The σ becomes almost zero when η_w is small because there are almost no pores exposed to the air at the ground surface. Considering the term E_{dir}, the upper boundary conditions are expressed as

$$-C_s\rho_s\lambda\left.\frac{\partial T_s}{\partial z}\right|_{z=0} = H_0 + lE_{dir} - R_{net}, \qquad (3\text{-}31)$$

for soil temperature,

$$-\left.\left(D_w\frac{\partial \eta_w}{\partial z} + K\right)\right|_{z=0} = -P_r + E_r + E_{dir}, \qquad (3\text{-}32)$$

for soil liquid water content, and

$$-\rho\varepsilon D_v(\eta_{ws} - \eta_w)\left.\frac{\partial q_s}{\partial z}\right|_{z=0} = -E_{dir} + E_0, \qquad (3\text{-}33)$$

for water vapor in the soil, respectively, where R_{net} and H_0 are the net radiation and sensible heat fluxes [W m^{-2}], P_r the precipitation [kg m^{-2}s^{-1}], E_r the surface runoff [kg m^{-2}s^{-1}], respectively. Note that only the latent heat by direct evaporation E_{dir} is included in Eq.(3-31) since the latent heat caused by phase change processes in the soil, E_b, are explicitly calculated at an each soil layer in the SOLVEG2. E_0 [kg m^{-2}s^{-1}] is water vapor flux from the pores with adsorbed water film to the atmosphere expressed by

$$E_0 = \rho(1-\sigma)c_{E0}|\mathrm{u}|(q_{s0} - q_r) \qquad (3\text{-}34)$$

where q_{s0} the specific humidity at the soil surface [kg kg^{-1}].

3.5. Surface runoff model

In the original SOLVEG2, total surface runoff can be calculated as an integration value of surface runoff per unit of time, E_r [kg m^{-2}s^{-1}], and is excluded from the object of SOLVEG2 calculation at each time step. In order to better represent the water budget at the ground surface, a sophisticated surface runoff model is incorporated to the modified model. It is assumed that E_r only occurs when water storage at the ground surface at the certain time (S_w [kg m^{-2}]) exceeds the water capacity of the ground surface (S_{wmax} [kg m^{-2}]); that is, $E_r = S_w - S_{wmax}$. S_{wmax} depends on surface characteristics and is mathematically described (Driessen 1986) [38] as

$$S_{w\max} = 0.5 z_r \frac{\sin^2(\sigma - \theta)}{\sin\sigma} \cdot \frac{\cot(\sigma + \theta) + \cot(\sigma - \theta)}{2\cos\sigma\cos\theta} \qquad (3\text{-}35)$$

where z_r is the surface roughness [mm], σ and θ the clod (or furrow) and slope angle of the land [degree], respectively. z_r and σ are set to have typical values for untilled land as 15 mm and 30° suggested by Driessen (1986) [38]. Using E_r, S_w at next time step (S_w*) is determined by the following equation of water balance at the ground surface for η_w

$$\frac{S_w^* - S_w}{dt} = E_{pr0} - E_w - E_r \qquad (3\text{-}36)$$

where E_{pr0} is the precipitation rate at the ground surface [kg m^{-2} s^{-1}], and E_w the water infiltration to the soil [kg m^{-2} s^{-1}] determined by the simple water balance model (Schaake et al. 1996) [39] used in the Noah Land Surface Model (Chen and Dudhia 2001) [40], respectively. Noted that evapo-transpiration is considered in water balance equation at the ground surface for specific humidity in soil.

4. Modifications of atmosphere and vegetation sub-models

4.1. Basic equations for cloud liquid water

In the atmosphere sub-model, there is a one-dimensional diffusion equation for cloud liquid water content in the atmosphere, w_f [kg kg^{-1}]

$$\frac{\partial w_f}{\partial t} = \frac{\partial}{\partial z}\left(K_z \frac{\partial w_f}{\partial z} + \frac{F_{sed}}{\rho} \right) - \frac{aE_{cap} + E_f + E_{col} - E_{pr}}{\rho}, \qquad (4\text{-}1)$$

where z is the height in the atmosphere [m], K_z the vertical turbulence diffusivity for w_f calculated by the turbulence closure model (Yamada 1981) [40] [m^2 s^{-1}], F_{sed} the gravitational flux of cloud water [kg m^{-2} s^{-1}], a the leaf area density at each canopy layer [m^{-2} m^{-3}], E_{cap} the capture rate of cloud water by leaves [kg m^{-2} s^{-1}], E_f evaporation or condensation rate of cloud water [kg m^{-3} s^{-1}], E_{col} and E_{pr} the capture rate of cloud water by rain droplets and the evaporation rate of rain droplets [kg m^{-3} s^{-1}], respectively.

The vegetation sub-model calculates the leaf surface water for each canopy layer, w_d [kg m^{-2}], vertical liquid water flux in the canopy, P_r [kg m^{-2} s^{-1}], and leaf temperature, T_c [K]. The w_d is determined by the following equation

$$\frac{\partial w_d}{\partial t} = E_{\text{int}} - E_d + E_{cap} - P_d, \qquad (4.2)$$

where E_{int} is the water exchange resulting from the interception of precipitation by leaves [kg m^{-2} s^{-1}], E_d the evaporation rate of leaf surface water [kg m^{-2} s^{-1}], and P_d the drip from leaves [kg m^{-2} s^{-1}], respectively. P_r is calculated by the following equation

$$\frac{\partial P_r}{\partial z} = a[E_d + E_s] + E_{pr} - E_{col}. \qquad (4.3)$$

The T_c is calculated by solving the leaf surface heat budget equation

$$R_c = H_c + l(E_d + E_s) + H_p, \qquad (4.4)$$

where R_c, H_c, E_s, and H_p are the net radiation, sensible heat flux [W m^{-2}], transpiration rate [kg m^{-2} s^{-1}], and cooling by precipitation [W m^{-2}], respectively. Each of these terms is determined by the leaf temperature and variables from the atmosphere and radiation sub-models.

4.2. Capture efficiency of cloud water droplets

Cloud water deposition on the canopy, E_{cap}, is expressed by the following equations

$$E_{cap} = \varepsilon F_f |\mathbf{u}| \rho w_f, \qquad (4.5)$$

and $$F_f = \frac{1 - \exp(-k_p a \Delta z)}{a \Delta z}, \qquad (4.6)$$

where ε is the capture efficiency of leaves for cloud water, F_f the shielding coefficient for cloud water in horizontal direction, $|\mathbf{u}|$ the wind speed [m s^{-1}], k_p the averaged projection coefficient of an individual leaf for cloud water, and Δz the thickness of canopy layer at height z [m], respectively. The average projection coefficient of radiation flux on an individual leaf was introduced in the original SOLVEG2 (Nagai 2003) [42]. In the present study, we applied this coefficient of radiation flux to cloud water (k_p). This results in the fact that F_f incorporates the decrease of effective leaf surface area intercepting cloud water below the total leaf area because of the inclination of leaf surface and the overlap of leaves. The original SOLVEG2 is based on the assumption that all cloud water droplet trajectories are perpendicular to the leaves and that the droplets are all captured, i.e., $\varepsilon = 1$. However, ε is usually < 1 because the droplets moving towards the leaf surfaces travel along curved streamlines that lead beyond the leaf, and only by loss of the inertia of the droplets, they are intercepted by leaves, according to a theory of droplet impaction. In the present study, ε is calculated with the following empirical function of the Stokes number S_{tk} (Peters and Eiden 1992) [43]

$$\varepsilon = \left(\frac{a_3 S_{tk}}{a_3 S_{tk} + a_1} \right)^{a_2}, \tag{4-7}$$

and $$S_{tk} = \frac{\rho_w d_p^2 |\mathbf{u}|}{9 \upsilon d_{leaf}}, \tag{4-8}$$

where a_1, a_2, and a_3 are fitting parameters, d_p the droplet diameter of cloud water [μm], ν the viscosity coefficient of air [kg m^{-1}s^{-1}], and d_{leaf} the characteristic leaf length [m], respectively. A summary of the parameters used in (4-7) for several plant species is given in Table 4-1.

Table 4-1 List of parameters for capture efficiency by Eq.(4-7).

Vegetation species	a_1	a_2	A_3	d_{leaf} (mm)	Reference
Needle leaf	5.0	1.05	1.0	1.0	Thorne et al. (1982) [44]
Broad leaf	0.5	1.90	5.0	30.0	Belot and Gauthier (1975) [45]
Grass	0.6	3.20	1.0	1.8	Chamberlain (1967) [46]
Crop	0.06	10.0	1.0	10.0	Aylor (1982) [47]
Others	5.0	1.05	1.0	1.0	Same as Needle leaf

4.3. Gravitational flux of cloud water

Total cloud water flux over the canopy is the sum of the turbulent flux, caused by atmospheric turbulent mixing, and the gravitational flux, F_{sed} in Eq.(4-1), which cannot be neglected when cloud droplets are large or wind speed is low (Lovett 1984) [48]. According to

Stokes' law, F_{sed} for each cloud water droplet is given as

$$F_{sed}\left(d_p\right)=\rho w_f\left(d_p\right)v_s\left(d_p\right), \tag{4-9}$$

and $$v_s\left(d_p\right)=\frac{g d_p\left(\rho_w-\rho\right)}{18\mu}, \tag{4-10}$$

where v_s is the sedimentation velocity of cloud water droplets [m s^{-1}], g the gravitational acceleration [m s^{-2}], and μ the viscosity of air [m^2 s^{-1}], respectively. Considering F_{sed}, E_{cap} for each cloud water droplet calculated by Eq. (4-5) can be expressed as

$$E_{cap}\left(d_p\right)=\left|\mathbf{u}\right|\rho w_f\left(d_p\right)\left[F_f\varepsilon\left(d_p\right)+F_v v_s\left(d_p\right)\right], \tag{4-11}$$

where F_v is the shielding coefficient for cloud water in the vertical direction, and is assumed to be equal to F_f.

4.4. Droplet size distribution of cloud water

Since E_{cap} varies with the droplet diameter of cloud water d_p, the droplet size distribution (DSD) is required for the calculation of ε for all cloud droplets. Since the DSD is generally a site-specific parameter and varies greatly with studies, several DSD parameterizations are introduced to the modified SOLVEG2. Best (1951) [49] suggested the following empirical formulation

$$g\left(d_p\right)=\left(\frac{n_B}{a_B}\right)\left(\frac{d_p}{a_B}\right)^{n_B-1}\exp\left(-\frac{d_p}{a_B}\right)^{n_B}, \tag{4-12}$$

with $$a_B=\max\left[1.0,\left(9.091\times10^5\rho w_f\right)^{0.559}\right], \tag{4-13}$$

where $g(d_p)$ is the probability density for cloud water droplets with d_p, n_B the empirical constant (n_B = 3.27). Lovett (1984) [48] used the parameterization in his model to quantify the amount of fog water deposition on the balsam fir forest.

The modified gamma distribution (Deirmendjian 1969) [50] is applied to describe the DSD

$$g\left(d_p\right)=a_D\left(\frac{d_p}{2}\right)^{p_D}\exp\left[-b_D\left(\frac{d_p}{2}\right)^{q_D}\right], \tag{4-14}$$

with $$b_D=\frac{p_D}{q_D\left(d_{\mathrm{mod}}/2\right)^{q_D}}, \tag{4-15}$$

where a_D, p_D, and q_D are the constants (a_D, p_D, q_D) = (3.041×10^{-4}, 4.0, 1.77), and b_D the function of d_{mod}, which is the mode diameter of droplet [μm], respectively. The d_{mod} is approximately equal to mean droplet diameter d_{mean} (= $17.03\rho w_f\times10^3+9.72$) [μm] which the author derived from the data collected at the Waldstein forest in Germany (Katata et al. 2008) [3].

Chaumerliac et al. (1987) [51] suggested the following expression using the d_{mean}

$$g(d_p) = \frac{N_D}{\sqrt{2\pi}\sigma_D d_p} \exp\left[-\frac{1}{2\sigma_D^2} \ln^2\left(\frac{d_p}{d_{mean}} \right) \right], \tag{4-16}$$

The above formulation has been used in the one-dimensional model for radiation fog and low-level stratiform clouds developed by Bott and Trautmann (2002) [52].

Klemm et al. (2005) [53] proposed the two log-normal distributions for eight classes of liquid water content

$$g(d_p) = \left[a_K \exp\left\{ -\frac{\left[\log_{10}(d_p/2) - b_K\right]^2}{c_K} \right\} + d_K \exp\left\{ -\frac{\left[\log_{10}(d_p/2) - e_K\right]^2}{f_K} \right\} \right] \Big/ LWC, \tag{4-17}$$

where a_K, b_K, c_K, d_K, e_K, f_K, and LWC are the constants given as Table 4-2.

Table 4-2 List of parameters for droplet size distribution by Eq.(4-17).

LWC (g m^{-3})	a_K (g m^{-3})	b_K	c_K	d_K (g m^{-3})	e_K	f_K
0.1	0.008	0.722	0.167	0.001	0.798	0.415
0.2	0.021	0.769	0.176	0.006	0.809	0.304
0.3	0.039	0.823	0.186	0.003	0.837	0.514
0.4	0.050	0.857	0.186	0.003	0.889	0.529
0.5	0.044	0.893	0.167	0.018	0.917	0.312
0.6	0.064	0.926	0.201	0.006	2.911	2.122
0.7	0.064	0.951	0.183	0.010	1.079	0.521
0.8	0.039	0.996	0.339	0.027	1.013	0.154

Considering the DSD, total capture of cloud water by leaves is represented by

$$E_{cap} = \int_{d_{p\min}}^{d_{p\max}} E_{cap}(d_p)\, dd_p, \tag{4-18}$$

where d_{pmax} and d_{pmin} are the maximum and minimum diameters among cloud water in all present cloud droplets [μm], set to $5 \times d_{mean}$ and 0 μm, respectively. In the modified SOLVEG2 model, hundred bins from d_{pmin} to d_{pmax}, each with an increment of 1 μm, are integrated.

4.5. Phase change processes for cloud water

To describe evaporation and condensation processes of cloud water, the following mass transfer sub-model was introduced in the modified SOLVEG2. The evaporation or condensation rate of cloud water droplets with d_p, $E_f(d_p)$, is determined by

$$E_f(d_p) = \rho k_f(d_p) A_f(d_p)[q_{sat}(T_a) - q_a], \tag{4-19}$$

where k_f (d_p) is the mass transfer coefficient for cloud droplets [m s^{-1}], A_f (d_p) the liquid-vapor interfacial area per weight of cloud water droplets [m^2 m^{-3}], and q_{sat} and q_a the saturated and air specific humidity [kg kg^{-1}], respectively. Assuming that all cloud water droplets are of spherical shape, $k_f(d_p)$ is calculated as follows

$$k_f(d_p) = (2D_v)/d_p, \tag{4-20}$$

where a value of 2 represents the Sherwood number of liquid water droplet at rest (Ranz and Marshall 1952) [54], and D_v the diffusion coefficient of water vapor [m^2 s^{-1}], respectively. Using the volume [$4/3\pi(d_p/2)^3$] and surface area of a cloud droplet [$4\pi(d_p/2)^2$], A_f (d_p) can be described as

$$A_f(d_p) = 4\pi(d_p/2)^2\left[\frac{\rho w_f(d_p)}{\rho_w(4/3)\pi(d_p/2)^3}\right] = \frac{6\rho w_f(d_p)}{\rho_w d_p}, \tag{4-21}$$

where the second term on the middle of Eq. (4-21) is the number density of cloud water droplets with d_p [m^{-3}]. Finally, total evaporation/condensation of cloud water E_f in Eq. (4.1) expressed as E_f (d_p) is integrated from d_{pmin} to d_{pmax}, using Eqs. (4.20) and (4.21), as in the case of the E_{cap} calculation.

4.6. Evaporation and condensation process on the leaf surface

The water vapor flux from leaf surface to the atmosphere is divided into two components; transpiration E_s and evaporation from leaf surface water E_d in Eq. (4-2), expressed as

$$E_s = \rho\frac{r_d}{R'}[q_{sat}(T_c) - q_a], \tag{4-22}$$

and $$E_d = \rho\frac{r_s}{R'}[q_{sat}(T_c) - q_a], \tag{4-23}$$

where $R' = (r_a r_s + r_a r_d + r_s r_d)$, and r_a, r_d, and r_s are evaporation resistances of the laminar leaf boundary layer, the leaf surface water, and the stomata of the leaves, respectively. r_a and the total of r_d and r_s are in series, but r_d and r_s are parallel because evaporation from leaf surface water and transpiration only occur from leaf surface water and stomata, respectively. r_s used in the model has been given by Nagai (2004) [1]. r_a is expressed using a generic transfer coefficient that accounts for the influence of wind speed and object shape and size estimated by mass transport theory (Magarey et al. 2005) [55] as

$$r_a = \left(c|\mathbf{u}|\right)^{-0.5}, \tag{4-24}$$

and $$c = c_w\left(w_d / w_{dw}\right) + c_d\left(1 - w_d / w_{dw}\right), \tag{4-25}$$

where w_{dw} is the leaf surface water amount where there is maximum evaporation (Deardorff 1978) [56] [kg m^{-3}], and c_w and c_d the vapor exchange coefficients between leaf and canopy air for wet and dry leaf surfaces, respectively [m$^{0.5}$ s$^{-0.5}$]. The value of c varies from c_w to c_d with a change of leaf wetness fraction (w_d/w_{dw}). The values of c_w and c_d were determined from the experiments of the drying of water droplets on an artificial leaf surface representing a typical hydrophobic leaf surface; the best estimates were 2.582 × 10^{-2} and 1.123 × 10^{-1} [m$^{0.5}$ s$^{-0.5}$], respectively (Magarey et al. 2005) [55]. The modified SOLVEG2 uses the formulation of r_d expressed as

$$r_d = \begin{cases} \left(1 - x_d\right)x_d^{-1} r_a & \left(q_{sat}\left(T_c\right) > q_a\right) \\ 0 & \left(q_{sat}\left(T_c\right) < q_a\right) \end{cases} \text{ with } x_d = \min\left[1, \left(w_d / w_{dw}\right)\right]^{2/3}. \tag{4-26}$$

When water partially exists on the leaf, the balance of E_s and E_d is controlled by total resistance of r_d and r_s connected in parallel. When the leaf is completely dry, r_d has the value of infinity because x_d representing leaf wetness fraction is zero; this results in E_d = 0 by Eq. (4-23). In contrast, when leaf surface is covered with water sufficiently ($w_d > w_{dw}$), r_d = 0 due to the fact that x_d = 1. As a result, E_s = 0 as calculated by Eq. (4-22).

5. Model code

The model code is written in fortran77 and 90, and executable on linux. The model has a function of parallel calculation by MPI. Test calculations have been done on PC cluster. Details of the model code and procedure to run the model are described here. Note that underlined files represent newly incorporated routines in the present study.

5.1. Structure of model code

The SOLVEG2 model mainly consists of the three directories of source code (SRC), input meteorological data (INPUT), and output directory (OUTPUT). Inside the SRC directory, the include files and modules, program files, model setting files, parameter files, and make files are found. Below are descriptions of the files and directories for a one dimensional calculation. The modules for three-dimensional and coupling calculations are described in the prior paper by Nagai (2004) [1].

a) Root directory: SOLVEG2/

- NQS shell-script	go_1D.sh
- Executable	zsolveg_1D.exe
- Parameter file	param_1D

b) Source code directory: SOLVEG2/SRC/

- Make shell-scripts	zmake_xxx
- Makefiles	zmakefile_xxx

- Include and module files (Incl*, prm_*)

- Inclcon1	Common blocks for constants and input meteorological data
- Inclcon2	Common blocks for constants defined in BLOCKDATA
- Inclnum	Parameters for grid numbers
- Inclnum_1D	Inclnum files for 1-D calculation
- Inclvari	Common blocks for variables
- <u>prm_soil</u>	Module for the dry soil model
- <u>prm_fog</u>	Module for fog deposition

- Program files (*.f)

- efalbedo.f	Subroutine EALBED: soil surface albedo
- ehws.f	Subroutine EHWS: saturated soil water content
- eli2va.f	Subroutine ELI2VA: specific humidity in soil pore
- eppara.f	Subroutine EPPARA: leaf projection coefficient
- espara.f	Subroutine ESPARA: soil heat capacity and conductivity

- evpara.f Subroutine EVPARA: soil vapor diffusivity/evaporation resistance
- ewpara.f Subroutine EWPARA: soil water conductivity and diffusivity
- faipsy.f Functions FAIM, FAIH, PSYM, PSYH, SHMD, and SHMDD: soil surface exchange functions
- fcpair.f Function FCPAIR: specific heat of air
- fcw.f Function FCW: specific heat of water
- feps.f Function EPS: Capture efficiency of cloud water droplets
  Function FDIST: Droplet size distribution (DSD) of cloud water
  Function DGL10: Gauss-Legendre quadrature integration
  Function DEIR: Deirmendjian parameterization of DSD
- fdensa.f Function FDENSA: air density
- fl.f Function FL: latent heat of vaporization
- gtable.f Subroutine GTABLE: soil parameters
- gvprofile.f Subroutine GVPROFILE: vegetation profile data
- gvtable.f Subroutine GVTABLE: vegetation parameters
- gzsolveg.f Subroutine GZSOLVEG: soil and vegetation grid
- gzsolveg.f_1D gzsolveg.f files for 1-D calculations
- main.f Main routine SOLVEG2
- main.f_1D main.f for 1-D calculation
- pblkd01.f BLOCK DATA: atmospheric parameters
- pdebugw0.f Subroutine DEBUGW: atmospheric variable output
- pfluxcal.f Subroutines SFPR13, FLXCAL, KMHCAL, and SAVEOD: turbulence and variable for the next time step
- pgener.f Subroutines GENER, DIREC1, and DIREC2: diffusion scheme
- pinit01.f Subroutine MSHINT: atmosphere grid
- pinit01.f_1D pinit01.f files for 1-D calculation
- pinitpf.f Subroutines INITPF and CLSL2A: initial atmospheric variables
- pmain03.f Subroutines UMAIN, TMAIN, EMAIN, and CMAIN: wind, temperature, specific humidity, fog water, turbulence, and CO_2
- ppcal.f Subroutine PCAL: air pressure
- ppread.f Subroutines PREAD and DEWTMP: parameters and initial data
- ppread.f_1D ppread.f files for 1-D calculations
- ptint.f Subroutine TIMEINT: boundary data
- ptint.f_1D ptint.f files for 1-D calculations
- shifi1.f Subroutine HIFI1: advection in soil
- slco2.f Subroutine SLCO2: soil CO_2
- sliqu.f Subroutine SLIQU: soil water
- solveg.f Subroutines SLVGIN and SOLVEG: soil and vegetation control

- solver1.f Subroutine SOLV1: diffusion scheme
- solver2.f Subroutine SOLV2: diffusion scheme
- srad.f Subroutine SFCRAD: canopy radiation transmission
- sradiatn.f Subroutine RADIATION: solar and long-wave radiation
- stemp.f Subroutine STEMP: soil temperature
- svapo.f Subroutine SVAPO: specific humidity in soil pore
- svfogcp.f Subroutine FOGCAP: cloud water collection rate by leaves
- svliqu.f Subroutine VLIQU: leaf surface water and canopy water flux
- svrsco2.f Subroutine RSCO2: CO_2 assimilation and stomatal resistance
- svrsst.f Subroutine RESISTS: stomatal resistance
- svsed.f Subroutine SED: gravitational flux of cloud water
- svtemp.f Subroutine VTEMP: vegetation temperature
- swadsp.f Subroutine WADSP0: water retention curve and phase change processes in the soil for the dry condition
  Subroutine LINEINT: Linear interpolation of data
  Function POTEV: potential surface evaporation

- Parameter files
  - Vertical grid files zmesh.model_1D
  - Soil parameter file for Brooks and Corey BCsoil.table (previously zsoil.table)
  - Soil parameter file for the dry soil model vGsoil.table
  - Vegetation profile file zvege.profile_1D
  - Vegetation parameter file zvege.table_1D

c) Input meteorological data directory: SOLVEG2/INPUT/
- Meteorology data file metdata.dat (file format is shown in Table 5-1)

Table 5-1 Meteorology data file for 1-D calculation: metdata.dat.

TIME	P	RS	RL	RR	U	V	T	Q	WL	CO2
1997-04-20_0015	964.36	108.28	317.14	0.00	-1.79	2.86	293.01	6.93	0.12	370.00
1997-04-20_0045	964.53	24.64	313.94	0.00	-1.75	2.41	291.96	6.81	0.32	370.00
… repeat until the end time of the calculation period										

P: surface pressure [hPa], RS: solar radiation flux [W m^{-2}], RL: long-wave radiation flux [W m^{-2}], RR: rain intensity [mm h^{-1}], U: wind u-component [m s^{-1}], V: wind v-component [m s^{-1}], T: air temperature [K], Q: specific humidity [g kg^{-1}], WL: cloud liquid water content [g m^{-3}], CO2: CO_2 concentration [ppmv].

d) Output data directory: SOLVEG2/OUTPUT/

- Input meteorological data file (fu23)	METout
- Surface flux file (fu24)	FLXout
- Wind speed file (fu25)	WNDout
- Atmospheric CO2 file (fu26)	ACO2out
- Atmospheric CO2 budget file (fu27)	BACO2out
- Soil variable file (fu30)	mnout
- Soil temperature file (fu31)	TSout
- Soil water content file (fu32)	HWout
- Soil humidity file (fu33)	QSout
- Soil evaporation file (fu34)	EBout
- Soil surface flux file (fu35)	SFout
- Canopy variable fale (fu40)	VGout
- Canopy water budget file (fu41)	VWout
- Canopy heat budget file (fu42)	VTout
- Canopy radiation file (fu43)	RADout
- Soil CO2 file (fu50)	SCO2out
- Canopy CO2 file (fu51)	VCO2out
- Accumulated fog and precipitation (fu52)	PREout
- Soil CO2 production file (fu52)	PSCO2out
- Soil CO2 budget file (fu53)	BSCO2out
- Atmospheric variable file (fu20)	dbout
- Standard output files (fu06)	outlist
- Water retention curve (fu36: only for IFDSL = 1)	wcurve

```
****************************************************************************************
Main     | Primary        | Secondary                        | Functions and libraries
----------------------------------------------------------------------------------------
SOLVEG2*
    ├---PREAD
    ├---MSHINT
    ├---SLVGIN* ┬---------------------------------------- SHMD
    |            ├-------GZSOLVEG
    |            ├-------GTABLE
    |            ├-------GVTABLE
    |            ├-------WADSPO
    |            ├-------LINEINT
    |            └-------GVPROFILE
    ├--- INITPF  ┬-------PCAL
    |            └-------CLSL2A
    ├---FLXCAL
    ├---SFPR13   ---------------------------------------- PSYM, PSYH
    ├---DEBUGW
(Start of time loop)
  ┌--┐
  ↑  ├--TIMEINT ┬
     |           ├-------DEWTMP ------------------------- SHMD
     |           └-------PCAL
     ├--KMHCAL
     ├--FLXCAL
     ├--SOLVEG* ┬---------------------------------------- PSYM, PSYH, SHMD, FL, FCPAIR
     |           ├-------DEWTMP ------------------------- SHMD
     |           ├-------GVPROFILE
     |           ├-------SFCRAD  ┬-------RADIATION
     |           |               └-------EPPARA
     |           ├-------SVAPO*  ┬----------------------- FDENSA, SHMD, FL
     |           |               ├-------EVPARA
     |           |               ├-------EHWS
     |           |               ├-------LINEINT
     |           |               └-------SOLV1
     |           ├-------SLIQU*  ┬-------EWPARA*---LINEINT
     |           |               └-------SOLV2
     |           ├-------STEMP*  ┬----------------------- FCPAIR, FCW, FL, POTEV
     |           |               ├-------ESPARA*--------- FCW
     |           |               ├-------EALBED
     |           |               └-------SOLV1
     |           ├-------SLCO2   ┬-------EHWS
     |           |               ├-------HIFI1
     |           |               └-------SOLVE2
     |           ├-------RSCO2   ------------------------ SHMD
     |           ├-------RESISTS ------------------------ SHMD
     |           ├-------VLIQU*  ┬----------------------- SHMD
     |           |               ├-------EPPARA
     |           |               └-------FOGCAP---------- EPS, FDIST, DGL10, DEIR, VGRV
     |           └-------VTEMP   ┬----------------------- FCPAIR, FCW, FL, SHMD, SHMDD
     |                           └-------EPPARA
     ├--SFPR13   ---------------------------------------- PSYM, PSYH
     ├--UMAIN    ----------------┬----------------------- PSYM
     |                           ├-------GENER
     |                           ├-------DIREC2
```

Continued on the following page.

```
   |                             └------SED------------FDIST, VGRV
   ├--TMAIN*  --------------┬--------------------- PSYM, PSYH, SHMD, FCPAIR, FL
   |                             ├------GENER
   |                             ├------DIREC2
   |                             └------ELI2VA  --------SHMD, SHMDD
   ├--EMAIN   --------------┬--------------------- FAIM
   |                             ├------GENER
   |                             └------DIREC1
   ├--CMAIN   --------------┬--------------------- PSYM, PSYH
   |                             ├------GENER
   |                             └------DIREC2
   ├--SAVEOD
   ├--DEBUGW
 ↑ |
 └-┘ (End of time loop)
  STOP
  END
*******************************************************************************************
```

Fig. 5-1 Calculation flow of the modified SOLVEG2. Underlined files are newly incorporated routines to the original SOLVEG2. Single asterisks are added to the routines modified in the present study. Note that the routines for MPI libraries and coupling modules for the Numerical Environmental System SPEEDI-MP are omitted in the flow.

5.2. Compiling the model

Before the model users go on to compile and run the model, the Inclnum_1D file at the SOLVEG2/SRC directory should be set to correct values of vertical grids for atmosphere (N1 and M1), vegetation (NC) and soil layers (NS). An example of this file is shown in Tables 5-2. Note that the number of vegetation layers are smaller than those of atmosphere; i.e., NC < N1. The numbers of total horizontal grids NX (x-direction) and NY (y-direction), and the grids for output file IX and JY are set to unity because of a one-dimensional calculation. The parameter NA should be set to the layer number where atmospheric variables are generated at the directory of SOLVEG2/OUTPUT. Under above settings, a compilation of the model is started by running the script of zmake_1D.sh at the SOLVEG2/SRC directory. After the execution of this script normally terminates, the execution file of SOLVEG2 named zsolveg_1D.exe must be created at the root directory SOLVEG2/.

Table 5-2 Model grid number setting file: Inclnum_1D.

```
      IMPLICIT DOUBLEPRECISION ( A-H , O-Z )
      PARAMETER ( N1 =  9 , M1 = N1+1 , N2 = 2*M1 )
      PARAMETER ( NS =  7 , NC =  9 )
      PARAMETER ( NX =  1 , NY =  1 )
      PARAMETER ( IX =  1 , JY =  1 , NA =  7 )
```

5.3. Running the model

Following the setting of grid number in the file of Inclnum_1D (Table 5-2), the vertical mesh sizes are edit in the zmesh.model_1D file (Table 5-3). In addition to this, an input file of hourly (or half hourly) meteorological data covering throughout the calculation period is necessary before the model execution (Table 5-1). In the source directory of SOLVEG2/SRC, the vegetation profile file (zvege.profile_1D: Table 5-4) needs to be modified to specify variations in the whole calculation period. In this file, vertical distributions of vegetation type (VTYPE), leaf area density (AZ), and root fraction for each vegetation type need to be specified. The vegetation type is chosen from the vegetation parameter file (zvege.table_1D), which is specified by two integers: the former represents the category of vegetation, and the latter the spatial or temporal variation of them.

Table 5-3 Model vertical grid setting file: zmesh.model_1D

```
SOLVEG Z-MESH DATA: 2002/02/12 CREATED BY NAGAI
SOIL LAYER         ZS(K) K=1,NS+1 : NS=7
  -0.000  -0.020  -0.050  -0.100  -0.200  -0.500  -1.000  -2.000
ATMOSPHERE LAYERS (M1) AND CANOPY LAYERS (NC)      Z(K) K=1,M1
     0.1     0.3     0.5     0.7     1.0     1.5     3.0     5.0     8.0    12.0
```

Table 5-4 Vegetation profile file: zvege.profile_1D.

```
***** DATA FORMATT ***********************************************************
*  yymmdd hrmnsc : DATE AND TIME -----------------------------------+ repeat  *
*   N : NUMBER OF LANDUSE CATEGORIES                                |         *
*   N1 / LANDUSE (COMMENTS)------------------------+ repeat N times |         *
*   VTYPE(K),K=1,NC : NO in zvege.tabele           |                |         *
*   AZ(K),K=1,NC    : leaf area density            |                |         *
*   L : number of VTYPE (ROOT FRACTION)            |                |         *
*   V1 RZ(K,V1),K=1,NS -------+ repeat L times     |                |         *
*     .....                                        |                |         *
*                                                  |                |         *
*  ---END OF THIS LANDUSE CATEGORY ----------------+                |         *
*   N2 / LANDUSE (COMMENTS)                                         |         *
*     .....                                                         |         *
*                                                                   |         *
*  ***END OF THIS TIME ---------------------------------------------+         *
*  yymmdd hrmnsc : DATE AND TIME                                              *
*     .....                                                                   *
```

Continued on the following page.

```
*                                                                            *
***** DATA FORMATT ***********************************************************
!!!!! DATA START !!!!!
030101 000000 : DATE AND TIME
 1 : NUMBER OF LANDUSE CATEGORIES
 1 / Canary Islands
    31    31    31    31    31    31    31
0.050 0.050 0.100 1.000 1.600 1.200 0.630
 1 : NUMBER OF ROOT (ROOT FRACTION)
  31   0.030   0.045   0.075   0.0925  0.2775   0.330   0.150
---END OF THIS LANDUSE CATEGORY
***END OF THIS TIME
030201 000000 : DATE AND TIME
 1 : NUMBER OF LANDUSE CATEGORIES
 1 / Canary Islands
    31    31    31    31    31    31    31
 0.050 0.050 0.150 1.200 1.800 2.200 0.800
 1 : NUMBER OF ROOT (ROOT FRACTION)
  31   0.030   0.045   0.075   0.0925  0.2775   0.330   0.150
---END OF THIS LANDUSE CATEGORY
***END OF THIS TIME
```
...repeat until the end time of the calculation period

In the parameter file (param_1D), the simulation condition such as calculation period, output interval is specified (Table 5-5). Parameters of DX, X00, and Y00 are meaningless for one-dimensional calculations.

Table 5-5 Sample parameter file: param_1D.

```
  IPRINT      =       1800<=========  ( S )   PRINT OUT INTERVAL      *
  GRTOP       =     3.5000000000D-03  (K/M)   V.P.T.G. AT MODEL TOP   *
  ROU         =     1.2000000000D+00  (KG/M3) AIR DENSITY             *
  TREF        =    12.0000000000D+00  (C)     REFERENCE TEMPERATURE   *
  TBOTOM      =    12.0000000000D+00  (C)     SOIL BOTTOM TEMPERATURE *
  TWATER      =    12.0000000000D+00  (C)     WATER TEMPERATURE       *
  EMSVTY      =     0.9800000000D-00  (     ) EMMISSIVITY OF G. SFC.  *
  ALBEDO      =     0.1400000000D-00  (     ) ALBEDO      OF G. SFC.  *
  TURBID      =     0.1000000000D-00  (  )    TURBIDITY OF AIR        *
  Z0          =     1.0000000000D-02  (M)     SURFACE ROUGHNESS (WIND)*
```
Continued on the following page.

```
  ZT          =     1.0000000000D-03  (M)      SURFACE ROUGHNESS (TEMP)*
 DELT         =    30.0000000000D+00  (S)      TIME INCREAMENT (S)     *
  LDATES      =  20030207<=========   (Y4M2D2) INITIAL DATE            *
  LTIMES      =    140000<=========   (H2M2S2) INITIAL TIME (STD.T.)   *
  TINTEGD     =   358.0000000000D+00  (DAY)    INTEGRATION PERIOD (DAY)*
  TINTEGH     =    10.0000000000D+00  (H)      INTEGRATION PERIOD (H)  *
  TINTINP     =  1800.0000000000D+00  (S)      INPUT DATA INTERVAL (S) *
  FLON        =    17.2330000000D+00  (DEG)    LONGITUDE               *
  FLAT        =    28.1670000000D+00  (DEG)    LATITUDE                *
  STDLON      =     0.0000000000D+00  (DEG)    LON. of STANDARD TIME   *
  STYPE       =    16.0000000000D+00  (     )  SOIL TEXTURE NUMBER     *
  UTYPE       =     1.0000000000D+00  (     )  LANDUSE TYPE NUMBER     *
  SFMOIS      =     0.6400000000D+00  (M3/M3)  SURFACE SOIL WATER CONT.*
  SBMOIS      =     0.3000000000D+00  (M3/M3)  SOIL BOTTOM WATER CONT. *
  SFTEMP      =   280.1600000000D+00  (K)      SOIL SURFACE TEMPERATURE*
  CO2AP       =     0.0000000000D+00  (ppm)    AIR CO2 CONCENTRATION + *
  CO2SI       =  5000.0000000000D+00  (ppm)    SOIL SURFACE CO2 CONC.  *
  SS0         =     0.0600000000D+00  (m-mol~) SOIL CO2 PRODUCTION RATE*
  SP0         =     0.0100000000D+00  (m-mol~) ROOT CO2 PRO. RATE / LAI*
  AAZ         =    10.5000000000D+00  (M-1)    SOIL CO2 PARAMETER      *
  DX          =     1.0000000000D+03  (M)      GRID INTERVAL           *
  X00         =-2673.0000000000D+03   (M)      X COORDINATE of SW-POINT*
  Y00         =-2673.0000000000D+03   (M)      Y COORDINATE of SW-POINT*
```

The model execution is done by submitting the NQS shell-script (go_1D.sh). Sample of the shell-script for three-dimensional MPI parallel calculation is shown in Table 5-6. The SOLVEG2 offers several options for CO2, fog, and soil models. Here we outline those available in the modified version.

a) iffog: fog deposition calculation (0 = no fog, 1 = include fog deposition)

b) npdsd: Droplet size distribution of cloud water when iffog = 1 (1 = Best [48], 2 = Deirmendjian [49], 3 = Caumerlic et al. [50], 4 = Klemm et al. [52])

c) ifdsl: Soil water retention curve and phase change processes of soil water (0 = do not include, 1 = include)

d) npwrc: Soil water retention curve when ifdsl = 0 (1 = old scheme by Brooks-Corey [18], 2 = new scheme of complete water retention curve based on van Genuchten [20] and Campbell and Shiozawa [21])

e) nptms: Soil thermal conductivity when ifdsl = 1 (1 = old scheme by McCumber and Pielke [13], 2 = new scheme using clay content by McInnes [15]) *f)* ifco2: CO_2 exchange process (0 = not include, 1 = include)

Table 5-6 Sample NQS shell-script for 3-D MPI parallel calculation: go_1D.sh.

```
#!/bin/csh -f
#######################################################
# SOLVEG grid calculation
#######################################################
#BSUB -J SOL1D
#BSUB -n 1
#BSUB -a intelmpi
#BSUB -o sol.out
#BSUB -e sol.err
#######################################################

set hmdir=$HOME/SOLVEG_1D
set srdir=${hmdir}"/SRC"
set indir=${hmdir}"/INPUT"
set otdir=${hmdir}"/OUTPUT"
set grdir=${hmdir}"/GRIDOUT"

# FOG CALCULATION (iffog) / 1:yes , 0:no
#
#  > iffog = 1: CHOOSE DSD PARAMETERIZATION  (npdsd=1-4)
#  > 1:BEST, 2: DEIRMENDJIAN(PRECISE BUT HEAVY),
#  > 3: CHAUMERLIAC, 4: KLEMM (EFFICTIVE SCHEME)
#
set iffog="1"
set npdsd="4"

# USE DRY SOIL MODEL (ifdsl) / 1:yes , 0:no
#
#  > ifdsl = 0: CHOOSE WATER RETENTION CURVE (nswrc=1-2)
#  > 1: OLD (B-C), 2: NEW (van-G + C-S COMPLETE CURVE)
#
#  > ifdsl = 1: CHOOSE SOIL THERMAL CONDUCT.(nstms=1-2)
#  > 1: OLD, 2: NEW (MCINNES 1981)
#
```
Continued on the following page.

```
set ifdsl="1"
set nswrc="2"
set nstms="2"

set ifco2="0"   # CO2 CALCULATION    / 1:yes , 0:no
set ifrst="0"   # RESTRT CALCULATION / 1:yes , 0:no

/bin/rm ${otdir}/*
#/bin/rm -r ${grdir}/grads
#/bin/rm -r ${grdir}/netcdf
#/bin/mkdir ${grdir}/grads
#/bin/mkdir ${grdir}/netcdf

#input files
setenv FORT10 ${hmdir}/param_1D
setenv FORT12 ${indir}/metdata.dat
setenv FORT14 ${srdir}/zmesh.model_1D
setenv FORT15 ${srdir}/BCsoil.table
setenv FORT16 ${srdir}/zvege.table_1D
setenv FORT17 ${srdir}/zvege.profile_1D
setenv FORT18 ${srdir}/vGsoil.table

#output files
#---in pzroot.f
setenv FORT20 ${otdir}/dbout
setenv FORT23 ${otdir}/METout
setenv FORT24 ${otdir}/FLXout
setenv FORT25 ${otdir}/WNDout
setenv FORT26 ${otdir}/ACO2out
setenv FORT27 ${otdir}/BACO2out

#---in solveg.f
setenv FORT30 ${otdir}/mnout
setenv FORT31 ${otdir}/TSout
setenv FORT32 ${otdir}/HWout
setenv FORT33 ${otdir}/QSout
setenv FORT34 ${otdir}/EBout
```
Continued on the following page.

```
setenv FORT35 ${otdir}/SFout
setenv FORT36 ${otdir}/wcurve

#---within the canopy
setenv FORT40 ${otdir}/VGout
setenv FORT41 ${otdir}/VWout
setenv FORT42 ${otdir}/VTout
setenv FORT43 ${otdir}/RADout

#---fog and precipitation
setenv FORT44 ${otdir}/PREout

#---CO2
setenv FORT50 ${otdir}/SCO2out
setenv FORT51 ${otdir}/VCO2out
setenv FORT52 ${otdir}/PSCO2out
setenv FORT53 ${otdir}/BSCO2out


#go
cd ${hmdir}

echo ${indir} >! EXpara_1D  # INPUT DATA PATH
echo ${grdir} >> EXpara_1D  # GRID  DATA PATH
echo ${iffog} >> EXpara_1D  # FOG CALCULATION
echo ${npdsd} >> EXpara_1D  # IFFOG -> DSD PARAM.
echo ${ifdsl} >> EXpara_1D  # USE ADSORPTION MODEL
echo ${nswrc} >> EXpara_1D  # WATER RETENTION CURVE
echo ${nstms} >> EXpara_1D  # SOIL THERMAL COND.
echo ${ifco2} >> EXpara_1D  # CO2 CALCULATION
echo ${ifrst} >> EXpara_1D  # RESTART CALCULATION

setenv FORT9 ${hmdir}/EXpara_1D

./zsolveg_1D.exe >& ${otdir}/outlist
/bin/rm EXpara_1D
```

6. Summary

In order to evaluate energy and water balances between atmosphere and land surface accurately, sophisticated physical schemes such as evaporation and adsorption processes in the soil and cloud (fog) water deposition on vegetation were implemented in the one-dimensional atmosphere-soil-vegetation model including CO_2 exchange process (SOLVEG2). The above schemes are designed to simulate processes in the atmosphere-soil-vegetation system under arid environment in a more realistic treatment of physical processes than the commonly used land surface models. Performance tests in arid areas showed that the above schemes have a significant effect on surface energy and water balances. The framework of the novel schemes for arid environments incorporated to SOLVEG2 was documented in the present paper.

The concept of further modifications of SOVLEG2 is summarized in Fig 6-1. In the future works, the processes of matter cycle due to atmospheric deposition (dry, wet and cloud water depositions) and plant uptake of nutrients, atmospheric pollutants, and radionuclide substances will be incorporated to the model for studies of material exchanges between atmosphere and land surface. The carbon exchanges between the vegetation and soil vegetation (such as litterfall) and stresses-growth-dynamics model which calculate biomass, LAI and canopy height from available organic substances and nutrients will be also implemented in the model. Meanwhile, the schemes of the snowfall interception by canopy and soil water freezing should be developed to adapt the model for cold environments. With such modifications made in the model, the model is suited to evaluate environmental loads to ecosystems, and their responses under extreme environmental conditions due to climate changes and human activities (e.g., global warming, air pollution, drought).

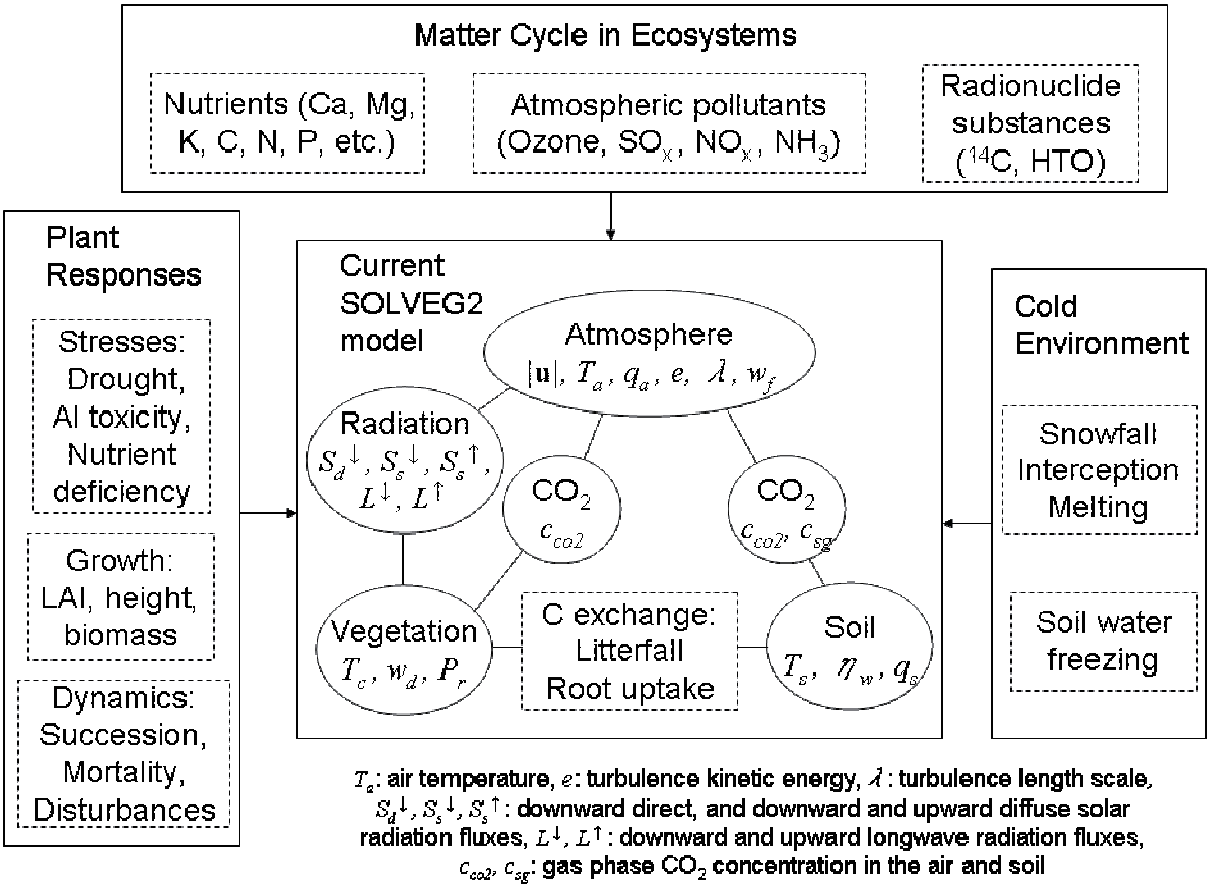

Fig.6-1 The concept of the atmosphere-soil-vegetation system based on the SOLVEG2. The modules squared with dashed lines will be developed in future works.

Acknowledgement

This research was performed using the computer system of Altix3700Bx2 in the Center for Computational Science and e-Systems. This study was also supported by the Research Revolution Plan 2002 (RR2002) of the Ministry of Education, Culture, Sports, Science, and Technology.

References

1) H. Nagai: "Atmosphere-soil-vegetation model including CO2 exchange processes: SOLVEG2", JAERI-Data/Code 2004-014 (2004).

2) G. Katata, H, Nagai, H. Ueda, N. Agam, P.R. Berliner: "Development of a Land Surface Model Including Evaporation and Adsorption Processes in the Soil for the Land-Air Exchange in Arid Regions", Journal of Hydrometeorology, 8, pp. 1307-1324 (2007).

3) G. Katata, H. Nagai, T. Wrzesinsky, O. Klemm, W. Eugster, R. Burkard: "Development of a Land Surface Model Including Cloud Water Deposition on Vegetation", Journal of Applied Meteorology and Climatology, 47, pp. 2129-2146 (2008).

4) N. Agam (Ninari), P.R. Berliner: "Dew formation and water vapor adsorption in semi-arid environments - A review", Journal of Arid Environments, 65, pp. 572-590 (2006).

5) A.F.G. Jacobs, B.G. Heusinkveld, S.M. Berkowicz: "Dew measurements along a longitudinal sand dune transect, Negev Desert, Israel", International Journal of Biometeorology, 43, pp. 184-190 (1999).

6) N. Agam (Ninari), P.R. Berliner, A. Zangvil, E. Ben Dor: "Soil water evaporation during the dry season in an arid zone", Journal of Geophysical Research, 109, D16103 (2004).

7) S.S.O. Burgess, T.E. Dawson: "The contribution of fog to the water relations of Sequoia sempervirens (D. Don): Foliar uptake and prevention of dehydration", Plant, Cell and Environment, 27, pp. 1023-1034 (2004).

8) L.B. Hutley, D. Doley, D.J. Yates, A. Boonsaner: "Water balance of an australian subtropical rainforest at altitude: The ecological and physiological significance of intercepted cloud and fog", Australian Journal of Botany, 45, pp. 311-329 (1997).

9) R.D. Jackson, R.J. Reginato, B.A. Kimball, F.S. Nakayama: "Diurnal soil-water evaporation: comparison of measured and calculated soil-water fluxes", Soil Science Society of America proceedings, 38, pp. 861-866 (1974).

10) J. Grifoll, J.Ma. Gastó, Y. Cohen: "Non-isothermal soil water transport and evaporation", Advances in Water Resources, 28, pp. 1254-1266 (2005).

11) J. R. Philip, D. A. De Vries: "Moisture movement in porous materials under temperature gradients", Transactions, American Geophysical Union, 38, pp. 222-232 (1957).

12) A. T. Cahill, M. B. Parlange: "On water transport in field soils", Water Resources Research, 34, pp. 731-739 (1998).

13) M. C. McCumber, R. A. Pielke: "Simulation of the effects of surface fluxes of heat and moisture in a mesoscale numerical model 1. Soil layer", Journal of Geophysical Research, 86, pp. 9929-9938 (1981).

14) C.D. Peters-Lidard, E. Blackburn, X. Liang, E.F. Wood: "The effect of soil thermal conductivity parameterization on surface energy fluxes and temperatures", Journal of the

Atmospheric Sciences, 55, pp. 1209-1224 (1998).
15) K. McInnes: "Thermal conductivities of soils from dryland wheat regions in eastern Washington", M.S. Thesis, Dept. of Agronomy and Soils, Washington State University, Pullman, WA, 51 p [Available from Owen Science Library, Washington State University, Pullman, WA 99163-3200.].
16) D.A. de Vries: "Thermal properties of soils", Physics of Plant Environment, 210-235, W.R. van Wijk North Holland Publ. Co., Amsterdam (1963).
17) W. Brutsaert: "Evaporation Into the Atmosphere", D. Reidel, 299 p (1982).
18) R.H. Brooks, A.T. Corey: "Hydraulic properties of porous media", Hydrology paper 3, Colorado State University, Fort Collins, 27 p (1964).
19) S. W. Webb: "A simple extension of two-phase characteristic curves to include the dry region", Water Resources Research, 36, pp. 1425-1430 (2000).
20) M.Th. van Genuchten: "Closed-form equation for predicting the hydraulic conductivity of unsaturated soils", Soil Science Society of America Journal, 44, pp. 892-898 (1980).
21) G.S. Campbell, S. Shiozawa: "Prediction of hydraulic properties of soils using particle-size distribution and bulk density data", International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils: 317-328, Univ. of Calif., Riverside, Calif (1992).
22) Y. Mualem: "New model for predicting the hydraulic conductivity of unsaturated porous media", Water Resources Research, 12, pp. 513-522 (1976).
23) R.F. Carsel, R.S. Parrish: "Developing joint probability distributions of soil water retention characteristics", Water Resources Research, 24, pp. 755-769 (1988).
24) J. Kondo, T. Watanabe: "Studies on the bulk transfer coefficients over a vegetated surface with a multilayer energy budget model", Journal of the Atmospheric Sciences, 49, pp. 2183-2199 (1992).
25) B.V. Derjaguin, N.V. Churaev: "On the question of determining the concept of disjoining pressure and its role in the equilibrium and flow of thin films", Journal of Colloid and Interface Science, 66, pp. 389-398 (1978).
26) M. Iwamatsu, K. Horii: "Capillary condensation and adhesion of two wetter surfaces", Journal of Colloid and Interface Science, 182, pp. 400-406 (1996).
27) D. Or, M. Tuller: "Liquid retention and interfacial area in variably saturated porous media: Upscaling from single-pore to sample-scale model", Water Resources Research, 35, pp. 3591-3605 (1999).
28) M. Tuller, O. Dani, L.M. Dudley: "Adsorption and capillary condensation in porous media: Liquid retention and interfacial configurations in angular pores", Water Resources Research, 35, pp. 1949-1964 (1999).
29) L.W. Petersen, P. Moldrup, O.H. Jacobsen, D.E. Rolston: "Relations between specific surface area and soil physical and chemical properties", Soil Science, 161, pp. 9-20 (1996).

30) A. Banin, A. Amiel: "A correlative study of the chemical and physical properties of a group of natural soils of Israel", Geoderma, 3, pp. 185-198 (1970).
31) K. Kosugi: "Three-parameter lognormal distribution model for soil water retention", Water Resources Research, 30, pp. 891-901 (1994).
32) S. Brunauer, P.H. Emmett, E. Teller: "Adsorption of gases in multimolecular layers", Journal of American Chemical Society, 60, pp. 309-319 (1938).
33) R.B. Bird, W.E. Stewart, E.N. Lightfoot: "Transport Phenomena", Wiley, 912 p (2001).
34) D.E. Rolston: "Gas flux", In: Klute, A. ed., "Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods", Agronomy Monograph No.9, American Society of Agronomy, Madison, pp. 1103-1119 (1986).
35) T.C. Ransohoff, C.J. Radke: "Laminar flow of a wetting liquid along the corners of a predominantly gas-occupied noncircular pore", Journal of Colloid and Interface Science, 121, pp. 392-401 (1988).
36) M.J. Blunt, H. Scher: "Pore-level modeling of wetting", Physical Review E, 52, pp. 6387-6403 (1995).
37) J.N. Israelachvili: "Intermolecular and Surface Forces, 2nd Ed.", Academic Press, London, 450 p (1992).
38) P.M. Driessen: "The water balance of the soil. In: Van Keulen H, Wolf J (Eds). Modelling of agricultural production: weather, soils and crops", Simulation Monographs, Pudoc,, Wageningen, pp. 76-116 (1986).
39) J.C. Schaake, V.I. Koren, Q.Y. Duan, K. Mitchell, F. Chen: "Simple water balance model for estimating runoff at different spatial and temporal scales", Journal of Geophysical Research, 101, pp. 7461-7475 (1996).
40) F. Chen, J. Dudhia: "Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity", Monthly Weather Review, 129, pp. 569-585 (2001).
41) T. Yamada: "A numerical simulation of nocturnal drainage flow", Journal of the Meteorological Society of Japan, 59, pp. 108-122 (1981).
42) H. Nagai: "Validation and sensitivity analysis of a new atmosphere-soil-vegetation model. Part II: Impacts on in-canopy latent heat flux over a winter wheat field determined by detailed calculation of canopy radiation transmission and stomatal resistance", Journal of Applied Meteorology, 42, pp. 434-451 (2003).
43) K. Peters, R. Eiden: "Modelling the dry deposition velocity of aerosol particles to a spruce forest", Atmospheric Environment, 26A, pp. 2555-2564 (1992).
44) P.G. Thorne, G.M. Lovett, W.A. Reiners: "Experimental determination of droplet impaction on canopy components of balsam fir", Journal of Applied Meteorology, 21, pp. 1413-1416 (1982).
45) Y. Belot, D. Gauthier: "Transport of micronic particles from atmosphere to folier

surfaces", Semin on Heat and Mass Transfer in the Environ of Veg, Heat and Mass Transfer in the Biosphere (Pt 1) pp. 583-591 (1975).
46) A.C. Chamberlain: "Transport of Lycopodium spores and other small particles to rough surfaces", Proceedings of the Royal Society of London Series A-Mathmatical Physical, 296, pp. 45-70 (1967).
47) D.E. Aylor: "Modeling spore dispersal in a barley crop", Agricultural Meteorology, 26, pp. 215-219 (1982).
48) G.M. Lovett: "Rates and mechanisms of cloud water deposition to a subalpine balsam fir forest", Atmospheric Environment, 18, pp. 361-371 (1984).
49) A.C. Best: "Drop-size distribution in cloud and fog", Quarterly Journal of the Royal Meteorological Society, 77, pp. 418-426 (1951).
50) D. Deirmendjian: "Electromagnetic Scattering on Spherical Polydispersions", Elsevier, New York, 290 p (1969).
51) N. Chaumerliac, E. Richard, J.-P., Pinty, E.C. Nickerson: "Sulfur scavenging in a mesoscale model with quasi-spectral microphysics: Two-dimensional results for continental and maritime clouds", Journal of Geophysical Research, 92, pp. 3114-3126 (1987).
52) A. Bott, T. Trautmann: "PAFOG - a new efficient forecast model of radiation fog and low-level stratiform clouds", Atmospheric Research, 64, pp. 191-203 (2002).
53) O. Klemm, T. Wrzesinsky, C. Scheer: "Fog water flux at a canopy top: Direct measurement versus one-dimensional model", Atmospheric Environment, 39, pp. 5375-5386 (2005).
54) W.E. Ranz, W.R. Marshall: "Evaporation from drops, Part II", Chemical Engineering Progress, 48, pp. 173-180 (1952).
55) R.D. Magarey, J.M. Russo, R.C. Seem, D.M. Gadoury: "Surface wetness duration under controlled environmental conditions", Agricultural and Forest Meteorology, 128, pp. 111-122 (2005).
56) J.W. Deardorff: "Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation", Journal of Geophysical Research, 83, pp. 1889-1903 (1978).

Appendix: Description of model code

The source files of the SOLVEG2 are described based on the categories of main routine, primary routines, secondary routines, and functions.

A-1 Main Routine

SOLVEG2 (main.f)

Function:

- Reading and setting the input and output directory paths and physics options for the dry soil model, fog deposition, CO_2 and restart calculations.
- Controlling calculation flow and time step.

Include files: Inclnum, Inclcon1, Inclcon2, Inclvari, prm_soil, prm_fog.

A-2 Primary Routines

PREAD (ppread.f)

Function:

- Reading parameters from param_1D.
- Reading initial data from files in the input directory.

Include files: Inclnum, Inclcon1, Inclcon2, Inclvari, prm_soil, prm_fog.

Variables: None.

MSHINT (NX, NY, N2, UTY, Z, ZZD) (main.f)

Function:

- Setting the atmosphere grid from data in zmesh.model_1D.

Include files: None.

Variables:

- NX:	Integer	Horizontal x-grid size.
- NY:	Integer	Horizontal y-grid size.
- N2:	Integer	Vertical grid size in the atmosphere.
- UTY(NX,NY):	Real*8	Land-use type [1 to 24 USGS categories].
- Z(NX,NY,N2):	Real*8	3-D grid height in the atmosphere [m].
- ZZD(NX,NY,N2):	Real*8	$[z(k+1)-z(k-1)]^{-1}$ [m^{-1}].

SLVGIN (ZI , DELTI , LDATEYI , TIMESI, LDATEI , LTIMEI , FLATI , TLAGLI , Z0I , ZTI, TBOTMI , TWATRI , TSI , HWI , STY, UTY, CO2SI, IFRST, PATHG, EMSVTYI, ALBEDOI , TURBIDI , PHPS, T0I , QS0I , CO20I , CTIME1 , ZSO) (solveg.f)

Function:

- Initializing soil and vegetation routines.

Include files: Inclnum, prm_soil.

Variables:

- ZI(NX,NY,N2):	Real*8	3-D grid height in the atmosphere [m].
- DELTI:	Real*8	Time increment [s].
- LDATEYI:	Integer	Julian day [day].
- TIMESI:	Real*8	Calculation start time [h].
- LDATEI:	Integer	Date [yyyymmdd].
- LTIMEI:	Integer	Time [hhmmss].
- FLATI(NX,NY):	Real*8	Latitude of model grid [deg.].
- TLAGLI(NX,NY):	Real*8	Local time difference from standard time [h].
- Z0I(NX,NY):	Real*8	Roughness height for momentum [m].
- ZTI(NX,NY):	Real*8	Roughness height for heat [m].
- TBOTMI(NX,NY):	Real*8	Soil bottom temperature [K].
- TWATRI(NX,NY):	Real*8	Sea surface temperature [K].
- TSI(NX,NY):	Real*8	Initial soil surface temperature [K].
- HWI(NX,NY):	Real*8	Initial soil water content [m^3 m^{-3}].
- STY(NX,NY):	Real*8	Soil type [1 to 16].
- UTY(NX,NY):	Real*8	Land-use type [1 to 24 USGS categories].
- CO2SI:	Real*8	Initial soil CO_2 concentration [ppmv].
- IFRST:	Integer	An index for restart calculations (0 or 1).
- PATHG:	Char.	The directory path for restart files.
- EMSVTYI(NX,NY):	Real*8	Surface emissivity.
- ALBEDOI(NX,NY):	Real*8	Surface albedo.
- TURBIDI(NX,NY):	Real*8	Turbidity of air.
- PHPS(NX,NY):	Real*8	Surface air pressure [hPa].
- T0I(NX,NY):	Real*8	Initial soil surface temperature [°C].
- QS0I(NX,NY):	Real*8	Initial soil surface specific humidity [kg kg^{-1}].
- CO20I(NX,NY):	Real*8	Initial soil surface CO_2 concentration [ppmv].
- CTIME1	Char*15	Calculation time [yyyy-mm-dd_hhmm].
- ZSO(NS+1)	Real*8	Soil grid depth [m].

INITPF (pinitpf.f)

Function:

- Initializing atmospheric variables.

Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.

Variables: None.

FLXCAL (pfluxcal.f)

Function:

- Calculating turbulent flux.

Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.

Variables: None.

SFPR13 (pfluxcal.f)

Function:

- Calculating stability, friction velocity and temperature.

Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.

Variables: None.

DEBUGW (IU, IS, IE, N, K1, K2, K3, K4, IPG) (pdebugw0.f)

Function:

- Outputting atmospheric variables.

Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.

Variables:

- IU: Integer File output unit number.
- IS: Integer Start layer number of output.
- IE: Integer End layer number of output.
- N: Integer Interval of output layers.
- K1: Integer Mean variable output flag [1: on, 0: off].
- K2: Integer Turbulence variable output flag [1: on, 0: off].
- K3: Integer Turbulence diffusivity output flag [1: on, 0: off].
- K4: Integer Turbulence term output flag [1: on, 0: off].
- IPG: Integer Paging flag.

TIMEINT (ptint.f)

Function:

- Reading boundary condition from files in the input directory or receive them from MM5.

- Interpolating input data into the model time step.

Include files: Inclnum, Inclcon1, Inclcon2, Inclvari, prm_fog.

Variables: None.

KMHCAL (pfluxcal.f)

Function:

- Calculating eddy diffusivity by level 2.5 turbulence closure model.

Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.

Variables: None.

SOLVEG (IFDBG, IFCO2, LDATEY, TIMEH, TIMET, LDATE, LTIME, ROU, PHPS, U, V, T, Q, WL, CO2, PRECIP, STBL, CNL, CNM, CNH, RSOL, RINF, RRATE, RSOLX, RINFX, T0, QS0, CO20, ALB, TEAS, FSH, FLH, FLQ, FGH, FLW, FNR, HWO, TSO, SOUV, SOTF, SOTA, SOQF, SOQA, SOWL, SOE2, AZCD, SOCO2, SS0, SP0, AAZ) (solveg.f)

Function:

- Controlling soil and vegetation routines.
- Interfacing atmosphere, soil, and vegetation sub-models.

Include files: Inclnum, prm_soil.

Variables:

- IFDBG:	Integer	Output flag [1: on, 0: off].
- IFCO2:	Integer	CO2 calculation flag [1: on, 0: off].
- LDATEY:	Integer	Julian day [day].
- TIMEH:	Real*8	Local time [h].
- TIMET	Real*8	Integration time [h].
- LDATE:	Integer	Date [yyyymmdd].
- LTIME:	Integer	Time [hhmmss].
- ROU(NX,NY):	Real*8	Air density [kg m^{-3}].
- PHPS(NX,NY):	Real*8	Surface air pressure [hPa].
- U(NX,NY,M1):	Real*8	Wind u-component [m s^{-1}].
- V(NX,NY,M1):	Real*8	Wind v-component [m s^{-1}].
- T(NX,NY,M1):	Real*8	Air temperature [°C].
- Q(NX,NY,M1):	Real*8	Specific humidity [kg kg^{-1}].
- WL(NX,NY,M1):	Real*8	Fog water content [kg kg^{-1}].
- CO2(NX,NY,M1):	Real*8	CO_2 concentration [ppmv].
- PRECIP(NX,NY):	Real*8	Precipitability [cm].
- STBL(NX,NY):	Real*8	Stability length [m].
- CNL(NX,NY):	Real*8	Low-level cloudiness [0 to 1 fraction].
- CNM(NX,NY):	Real*8	Middle-level cloudiness [0 to 1 fraction].
- CNH(NX,NY):	Real*8	High-level cloudiness [0 to 1 fraction].
- RSOL(NX,NY):	Real*8	Solar radiation flux [W m^{-2}].
- RINF(NX,NY):	Real*8	Long-wave radiation flux [W m^{-2}].
- RRATE(NX,NY):	Real*8	Rain intensity [mm h^{-1}].
- RSOLX(NX,NY):	Real*8	Model solar radiation flux [W m^{-2}].
- RINFX(NX,NY):	Real*8	Model long-wave radiation flux [W m^{-2}].

- T0(NX,NY): Real*8 Soil surface temperature [°C].
- QS0(NX,NY): Real*8 Soil surface specific humidity [kg kg^{-1}].
- CO20(NX,NY): Real*8 Soil surface CO_2 concentration [ppmv].
- ALB(NX,NY): Real*8 Surface albedo.
- TEAS(NX,NY): Real*8 Energy consumption by photosynthesis [W m^{-2}].
- FSH(NX,NY): Real*8 Sensible heat flux [W m^{-2}].
- FLH(NX,NY): Real*8 Latent heat flux [W m^{-2}].
- FLQ(NX,NY): Real*8 Vapor flux [kg m^{-2} s^{-1}].
- FGH(NX,NY): Real*8 Soil heat flux [W m^{-2}].
- FLW(NX,NY): Real*8 Upward long-wave radiation flux [W m^{-2}].
- FNR(NX,NY): Real*8 Net radiation [W m^{-2}].
- HWO(NX,NY,NS): Real*8 Soil water content [m^3 m^{-3}].
- TSO(NX,NY,NS): Real*8 Soil temperature [K].
- SOUV(NX,NY,M1): Real*8 Momentum exchange term by vegetation [s^{-1}].
- SOTF(NX,NY,M1): Real*8 Heat source term by vegetation [K s^{-1}].
- SOTA(NX,NY,M1): Real*8 Heat exchange term by vegetation [s-1].
- SOQF(NX,NY,M1): Real*8 Vapor source term by vegetation [kg kg^{-1} s^{-1}].
- SOQA(NX,NY,M1): Real*8 Vapor exchange term by vegetation [s-1].
- SOWL(NX,NY,N1): Real*8 Fog source term by vegetation [kg kg^{-1} s^{-1}].
- SOE2(NX,NY,M1): Real*8 Turbulence source term by vegetation [$m^{0.5}$ $s^{-1.5}$].
- AZCD(NX,NY,M1): Real*8 $a \times c_D$ [m^2 m^{-3}].
- SOCO2(NX,NY,M1): Real*8 CO_2 source term by vegetation [ppmv s^{-1}].
- SS0: Real*8 Optimal soil CO_2 production rate [μmol m^{-2} s^{-1}].
- SP0: Real*8 Optimal root CO_2 production rate [μmol m^{-2} s^{-1}].
- AAZ: Real*8 CO_2 production distribution parameter in the soil [m^{-1}].

UMAIN (SOUV) (pmain03.f)

Function:

- Calculating wind components u and v.

Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.

Variables:

- SOUV(NX,NY,M1): Real*8 Momentum exchange term by vegetation [s^{-1}].

TMAIN (SOTF, SOTA, SOQF, SOQA, SOWL) (pmain03.f)

Function:

- Calculating temperature, specific humidity, and fog water.

Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.

Variables:

- SOTF(NX,NY,M1):	Real*8	Heat source term by vegetation [K s^{-1}].
- SOTA(NX,NY,M1):	Real*8	Heat exchange term by vegetation [s-1].
- SOQF(NX,NY,M1):	Real*8	Vapor source term by vegetation [kg kg^{-1} s^{-1}].
- SOQA(NX,NY,M1):	Real*8	Vapor exchange term by vegetation [s-1].
- SOWL(NX,NY,N1):	Real*8	Fog source term by vegetation [kg kg^{-1} s^{-1}].

EMAIN (SOE2) (pmain03.f)

Function:

- Calculating turbulence energy and length scale.

Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.

Variables:

- SOE2(NX,NY,M1):	Real*8	Turbulence source term by vegetation [$m^{0.5}$ $s^{-1.5}$].

CMAIN (SOCO2) (pmain03.f)

Function:

- Calculating atmospheric CO_2 concentration.

Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.

Variables:

- SOCO2(NX,NY,M1):	Real*8	CO_2 source term by vegetation [ppmv s^{-1}].

SAVEOD (AZCD) (pfluxcal.f)

Function:

- Setting variables for the next time step.
- Calculating the top boundary values of turbulence energy and length scale.

Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.

Variables:

- AZCD(NX,NY,M1):	Real*8	$a \times c_D$ [m^2 m^{-3}].

A-3 Secondary Routines

GZSOLVEG (NX, NY, NS, NC, UTY, ZS, ZC) (gzsolveg.f)

Function:

- Setting soil and vegetation grids from data in zmesh.grid_3D and zmesh.model_1D/3D.

Include files: None.

Variables:

- NX:	Integer	Horizontal x-grid size.

- NY:	Integer	Horizontal y-grid size.
- NS:	Integer	Vertical grid size in soil.
- NC:	Integer	Vertical grid size in vegetation canopy.
- UTY(NX,NY):	Real*8	Land-use type [1 to 24 USGS categories].
- ZS(0:NS+1):	Real*8	Vertical grid in soil [m].
- ZC(NX,NY,0:NC+1):	Real*8	3-D grid height in vegetation canopy [m].

GTABLE (gtable.f)

Function:

- Setting soil parameter from data in zoil.table.

Include files: None.

Variables: None.

GVTABLE (CHANGD, CHANGEH, CHANGEE, WDSAT, WDEVP, FANGLE, REFLECT, TRANSMT, EMISSIV, RSSTMIN, PARCRT, FGRVGE, VMAX25, SLOPE) (gvtable.f)

Function:

- Setting vegetation parameter from data in zvege.table_1D/3D.

Include files: None.

Variables:

- CHANGD(0:99):	Real*8	Aerodynamic resistance of leaf.
- CHANGEH(0:99):	Real*8	Heat exchange coefficient between leaf and air.
- CHANGEE(0:99):	Real*8	Vapor exchange coefficient between leaf and air.
- WDSAT(0:99):	Real*8	Maximum leaf surface water [kg m^{-2}].
- WDEVP(0:99):	Real*8	Leaf surface water for max. evaporation [kg m^{-2}].
- FANGLE(0:99):	Real*8	Mean zenith angle of leaf orientation [deg.].
- REFLECT(2,0:99):	Real*8	Leaf reflectivity for visible and near-infrared.
- TRANSMT(2,0:99):	Real*8	Leaf transmissivity for visible and near-infrared.
- EMISSIV(0:99):	Real*8	Leaf emissivity.
- RSSTMIN(0:99):	Real*8	Minimum stomatal resistance [s m^{-1}].
- PARCRT(0:99):	Real*8	Critical value of PAR [W m^{-2}].
- FGRVGE(0:99):	Real*8	Green leaf fraction [0 to 1 fraction].
- VMAX25(0:99):	Real*8	V_m at 25 °C [μmol m^{-2} s^{-1}].
- SLOPE (0:99):	Real*8	Empirical constant m for stomatal resistance.

WADSP0 (swadsp.f)

Function:

- Calculating water retention curve and phase change processes in the soil.

Include files: Inclnum and prm_soil.

Variables: None.

LINEINT (X, Y, XX, YY, N) (swadsp.f)

Function:

- Linearly interpolating the data.

Include files: prm_soil.

Variables:

- MAXA:	Integer	Maximum number of arrays.
- X:	Real*8	Target of x value.
- Y:	Real*8	Target of y value.
- XX(0:MAXA):	Real*8	X arrays for linear interpolation.
- YY(0:MAXA):	Real*8	Y arrays for linear interpolation.
- N:	Integer	Number of interpolation data.

GVPROFILE (NS, NC, IDATEV, ITIMEV, VTYPEI, AZI, RZI) (gvprofile.f)

Function:

- Setting vegetation profile from data in zvege.profile_1D/3D.

Include files: None.

Variables:

- NS:	Integer	Vertical grid size in soil.
- NC:	Integer	Vertical grid size in vegetation canopy.
- IDATEV:	Integer	Date in vegetation profile data [yymmdd].
- ITIMEV:	Integer	Time in vegetation profile data [hhmmss].
- VTYPEI(0:NC,30,2):	Integer	Vegetation type.
- AZI(0:NC,30,2):	Real*8	Leaf area density [m^2 m^{-3}].
- RZI(0:NC,0:NS,30,2):	Real*8	Root distribution [0 to 1 fraction].

PCAL (ppcal.f)

Function:

- Calculating air pressure profile.

Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.

Variables: None.

CLSL2A (pinitpf.f)

Function:

- Calculating turbulence variables by level 2.0 turbulence closure model.

Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.

Variables: None.

DEWTMP (QA, PHPS, TDEW) (ppread.f)

Function:

- Calculating dew temperature from specific humidity.

Include files: None.

Variables:

- QA	Real*8	Specific humidity [kg kg^{-1}].
- PHPS	Real*8	Air pressure [hPa].
- TDEW	Real*8	Dew temperature [K].

SFCRAD (ZC, AZ, FLAT, TLAGL, LDATEY, TIMEH, CNL, CNM, CNH, RSOL, RINF, PHPS, EMSVTY, ALBEDOD, ALBEDOS, PRECIP, TURBID, REFLECT, TRANSMT, EMISSIV, FANGLE, ROU, T, WL, TTC, WLC, TC, T0, PR, VF, RDDN, RSDN, RSUP, RLDN, RLUP, PARABS, SUNABS, FLIT, HR, ZENITH, RSMX, RSOLX, RINFX) (srad.f)

Function:

- Calculating radiation transmission in vegetation canopy.

Include files: Inclnum.

Variables:

- ZC(NX,NY,0:NC+1):	Real*8	3-D grid height in vegetation canopy [m].
- AZ(NX,NY,0:NC):	Real*8	Leaf area density [m^2 m^{-3}].
- FLAT(NX,NY):	Real*8	Latitude of model grid [deg.].
- TLAGL(NX,NY):	Real*8	Local time difference from standard time [h].
- LDATEY:	Integer	Julian day [day].
- TIMEH:	Real*8	Local time [h].
- CNL(NX,NY):	Real*8	Low-level cloudiness [0 to 1 fraction].
- CNM(NX,NY):	Real*8	Middle-level cloudiness [0 to 1 fraction].
- CNH(NX,NY):	Real*8	High-level cloudiness [0 to 1 fraction].
- RSOL(NX,NY):	Real*8	Solar radiation flux [W m^{-2}].
- RINF(NX,NY):	Real*8	Long-wave radiation flux [W m^{-2}].
- PHPS(NX,NY):	Real*8	Surface air pressure [hPa].
- EMSVTY(NX,NY):	Real*8	Surface emissivity.
- ALBEDOD(2,NX,NY):	Real*8	Surface albedo for direct solar radiation.
- ALBEDOS(2,NX,NY):	Real*8	Surface albedo for diffuse solar radiation.
- PRECIP(NX,NY):	Real*8	Precipitability [cm].
- TURBID(NX,NY):	Real*8	Turbidity of air.
- REFLECT(2,NX,NY,0:NC):	Real*8	Leaf reflectivity for visible and near-infrared.

- TRANSMT(2,NX,NY,0:NC): Real*8 Leaf transmissivity for visible and near-infrared.
- EMISSIV(NX,NY,0:NC): Real*8 Leaf emissivity.
- FANGLE(NX,NY,0:NC): Real*8 Mean zenith angle of leaf orientation [deg.].
- ROU(NX,NY): Real*8 Air density [kg m^{-3}].
- T(NX,NY,M1): Real*8 Air temperature [°C].
- WL(NX,NY,M1): Real*8 Fog water content [kg kg^{-1}].
- TTC(NX,NY,0:NC): Real*8 Canopy air temperature [°C].
- WLC(NX,NY,0:NC): Real*8 Canopy air fog water content [kg kg^{-1}].
- TC(2,NX,NY,0:NC): Real*8 Temperature for sun-lit/shaded leaf [°C].
- T0(NX,NY): Real*8 Soil surface temperature [°C].
- PR(NX,NY,0:NC): Real*8 Vertical water flux in canopy [kg m^{-2} s^{-1}].
- VF(NX,NY): Real*8 Vertical speed of precipitation [m s^{-1}].
- RDDN(2,NX,NY,0:NC): Real*8 Downward direct solar radiation flux [W m^{-2}].
- RSDN(2,NX,NY,0:NC): Real*8 Downward diffuse solar radiation flux [W m^{-2}].
- RSUP(2,NX,NY,0:NC): Real*8 Upward diffuse solar radiation flux [W m^{-2}].
- RLDN(2,NX,NY,0:NC): Real*8 Downward long-wave radiation flux [W m^{-2}].
- RLUP(2,NX,NY,0:NC): Real*8 Upward long-wave radiation flux [W m^{-2}].
- PARABS(2,NX,NY,NC): Real*8 PAR absorbed by leaves [W m^{-2}].
- SUNABS(2,NX,NY,NC): Real*8 Solar radiation absorbed by leaves [W m^{-2}].
- FLIT(NX,NY,NC): Real*8 Fraction of sun-lit leaves [0 to 1 fraction].
- HR(NX,NY,0:NC): Real*8 Heating of canopy air by radiation [J m^{-3} s^{-1}].
- ZENITH(NX,NY): Real*8 Solar zenith angle [deg.].
- RSMX: Real*8 Maximum solar radiation flux [W m^{-2}].
- RSOLX(NX,NY): Real*8 Model solar radiation flux [W m^{-2}].
- RINFX(NX,NY): Real*8 Model long-wave radiation flux [W m^{-2}].

RADIATION (DFLAT, TLAGL, DSLAT, TIME, PRECIP, TURBID, ALBEDO, TEMP, CNL, CNM, CNH, ZENITH, RSMX, RSOLX, RINFX) (sradiatn.f)

Function:

- Calculating solar and long-wave radiation flux.

Include files: None.

Variables:

- DFLAT: Real*8 Latitude [deg.].
- TLAGL: Real*8 Local time difference from standard time [h].
- DSLAT: Real*8 Solar latitude [deg.].
- TIME: Real*8 Model time [h].
- PRECIP: Real*8 Precipitability [cm].
- TURBID: Real*8 Turbidity of air.

- ALBEDO:	Real*8	Surface albedo.
- TEMP:	Real*8	Surface layer temperature [K].
- CNL:	Real*8	Low-level cloudiness [0 to 1 fraction].
- CNM:	Real*8	Middle-level cloudiness [0 to 1 fraction].
- CNH:	Real*8	High-level cloudiness [0 to 1 fraction].
- ZENITH:	Real*8	Solar zenith angle [deg.].
- RSMX:	Real*8	Maximum solar radiation flux [W m^{-2}].
- RSOLX:	Real*8	Model solar radiation flux [W m^{-2}].
- RINFX:	Real*8	Model long-wave radiation flux [W m^{-2}].

EPPARA (NC, DZC, AZ, FA, FR) (eppara.f)

Function:

- Calculating shielding coefficient of canopy layers.

Include files: None.

Variables:

- NC:	Integer	Vertical grid size in vegetation canopy.
- DZC(0:NC):	Real*8	Depth of vegetation layers [m].
- AZ(0:NC):	Real*8	Leaf area density [m^2 m^{-3}].
- FA(0:NC):	Real*8	Mean projection coefficient of leaves.
- FR(0:NC):	Real*8	Shielding coefficient of canopy layers.

SVAPO (Z, TEXTURE, MYU, DELT, PHPS, TR, UR, QR, CE0, AIRDEN, HW, EB, T, QS, VFS, RES) (svapo.f)

Function:

- Calculating vapor transport in soil.

Include files: Inclnum, prm_soil.

Variables:

- Z(0:NS+1):	Real*8	Vertical grid in soil [m].
- TEXTURE(NX,NY,0:NS):	Integer	Soil type [1 to 24 USGS soil type].
- MYU:	Real*8	Parameter for numerical scheme.
- DELT:	Real*8	Time increment [s].
- PHPS(NX,NY):	Real*8	Surface air pressure [hPa].
- TR(NX,NY):	Real*8	Lowest atmosphere layer temperature [K].
- UR(NX,NY):	Real*8	Lowest atmosphere layer wind speed [m s^{-1}].
- QR(NX,NY):	Real*8	Lowest atmosphere layer humidity [kg kg^{-1}].
- CE0(NX,NY):	Real*8	Vapor exchange coefficient at soil surface.
- AIRDEN(NX,NY):	Real*8	Air density [kg m^{-3}].
- HW(NX,NY,0:NS):	Real*8	Soil water content [m^3 m^{-3}].

- EB(NX,NY,0:NS):	Real*8	Evaporation rate of soil water [kg m^{-3} s^{-1}].
- T(NX,NY,0:NS):	Real*8	Soil temperature [K].
- QS(NX,NY,0:NS):	Real*8	Specific humidity of soil pore [kg kg^{-1}].
- VFS(NX,NY,0:NS):	Real*8	Vapor flux in soil [kg m^{-2} s^{-1}].
- RES(NX,NY):	Real*8	Soil surface water [kg m^{-2}].

SOLVE1 (NX, NY, NZ, A, B, C, D, Q, WK1, WK2) (solver1.f)

Function:

- Numerical scheme for diffusion equation in soil with constant bottom boundary.

Include files: None.

Variables:

- NX:	Integer	Horizontal x-grid size.
- NY:	Integer	Horizontal y-grid size.
- NZ:	Integer	Vertical grid size.
- A(NX,NY,0:NZ):	Real*8	Coefficient (7-8) in the numerical scheme.
- B(NX,NY,0:NZ):	Real*8	Coefficient (7-9) in the numerical scheme.
- C(NX,NY,0:NZ):	Real*8	Coefficient (7-10) in the numerical scheme.
- D(NX,NY,0:NZ):	Real*8	Coefficient (7-11) in the numerical scheme.
- Q(NX,NY,0:NZ):	Real*8	Solution.
- WK1(NX,NY,0:NZ):	Real*8	Temporal variable.
- WK2(NX,NY,0:NZ):	Real*8	Temporal variable.

EVPARA (NX, NY, NS, TEXTURE, HW, T, CDIF, RB) (evpara.f)

Function:

- Calculating vapor diffusivity in soil and evaporation resistance of soil water.

Include files: None.

Variables:

- NX:	Integer	Horizontal x-grid size.
- NY:	Integer	Horizontal y-grid size.
- NS:	Integer	Vertical grid size in soil.
- TEXTURE(NX,NY,0:NS):	Integer	Soil type [1 to 24 USGS soil type].
- HW(NX,NY,0:NS):	Real*8	Soil water content [m^3 m^{-3}].
- T(NX,NY,0:NS):	Real*8	Soil temperature [K].
- CDIF(NX,NY,0:NS):	Real*8	Vapor diffusivity in soil [m^2 s^{-1}].
- RB(NX,NY,0:NS):	Real*8	Evaporation resistance of soil water [s m^{-1}].

EHWS (NX, NY, NS, TEXTURE, HWS) (ehws.f)

Function:

- Setting saturated soil water content.

Include files: None.

Variables:

- NX:	Integer	Horizontal x-grid size.
- NY:	Integer	Horizontal y-grid size.
- NS:	Integer	Vertical grid size in soil.
- TEXTURE(NX,NY,0:NS):	Integer	Soil type [1 to 24 USGS soil type].
- HWS(NX,NY,0:NS):	Real*8	Saturated soil water content [m^3 m^{-3}].

SLIQU (Z, TEXTURE, MYU, DELT, ET, PR0, HW, EB, ER, T, RES, VFS, WF, WFR, IFLGFEED) (sliqu.f)

Function:

- Calculating water transport in soil.

Include files: Inclnum, prm_soil.

Variables:

- Z(0:NS+1):	Real*8	Vertical grid in soil [m].
- TEXTURE(NX,NY,0:NS):	Integer	Soil type [1 to 24 USGS soil type].
- MYU:	Real*8	Parameter for numerical scheme.
- DELT:	Real*8	Time increment [s].
- ET(NX,NY,0:NS):	Real*8	Root uptake (transpiration) rate [kg m^{-3} s^{-1}].
- PR0(NX,NY):	Real*8	Precipitation intensity at soil surface [kg m^{-2} s^{-1}].
- HW(NX,NY,0:NS):	Real*8	Soil water content [m^3 m^{-3}].
- EB(NX,NY,0:NS):	Real*8	Evaporation rate of soil water [kg m^{-3} s^{-1}].
- ER(NX,NY,0:NS):	Real*8	Runoff [kg m^{-2} s^{-1}(surface), kg m^{-3} s^{-1}(in-soil)].
- T(NX,NY,0:NS):	Real*8	Soil temperature [K].
- RES(NX,NY):	Real*8	Soil surface water [kg m^{-2}].
- VFS(NX,NY,0:NS):	Real*8	Vapor flux in soil [kg m^{-2} s^{-1}].
- WF(NX,NY,0:NS):	Real*8	Water flux in soil [kg m^{-2} s^{-1}].
- WFR(NX,NY):	Real*8	Soil bottom water up-flow [kg m^{-2} s^{-1}].
- IFLGFEED:	Integer	Hydrology model coupling flag [1: on, 0: off].

SOLVE2 (NX, NY, NZ, A, B, C, D, Q, WK1, WK2) (solver2.f)

Function:

- Numerical scheme for diffusion equation in soil with variable bottom boundary.

Include files: None.

Variables:

- NX:	Integer	Horizontal x-grid size.
- NY:	Integer	Horizontal y-grid size.

- NZ: Integer Vertical grid size.
- A(NX,NY,0:NZ): Real*8 Coefficient (7-8) in the numerical scheme.
- B(NX,NY,0:NZ): Real*8 Coefficient (7-9) in the numerical scheme.
- C(NX,NY,0:NZ): Real*8 Coefficient (7-10) in the numerical scheme.
- D(NX,NY,0:NZ): Real*8 Coefficient (7-11) in the numerical scheme.
- Q(NX,NY,0:NZ): Real*8 Solution.
- WK1(NX,NY,0:NZ): Real*8 Temporal variable.
- WK2(NX,NY,0:NZ): Real*8 Temporal variable.

EWPARA (NX, NY, NS, TEXTURE, HW, DW, DDW, KW, DKW) (ewpara.f)

Function:

- Calculating diffusivity and hydraulic conductivity of soil water.

Include files: prm_soil.

Variables:

- NX: Integer Horizontal x-grid size.
- NY: Integer Horizontal y-grid size.
- NS: Integer Vertical grid size in soil.
- TEXTURE(NX,NY,0:NS): Integer Soil type [1 to 24 USGS soil type].
- HW(NX,NY,0:NS): Real*8 Soil water content [m^3 m^{-3}].
- DW(NX,NY,NS): Real*8 Soil water diffusivity [m^2 s^{-1}].
- DDW(NX,NY,NS): Real*8 Derivative of soil water diffusivity [m s^{-1}].
- KW(NX,NY,NS+1): Real*8 Hydraulic conductivity of soil [m s^{-1}].
- DKW(NX,NY,NS+1): Real*8 Derivative of hydraulic conductivity of soil [s^{-1}].

STEMP (Z, TEXTURE, MYU, DELT, ZENITH, RS, RSD, RSS, RL, TR, UR, QR, CH0, AIRDEN, PR0, TP, HTOPF, HRADF, HTOPL, HGTOP, HW, EB, T, RES, VFS, ALBDD, ALBDS, EMIS) (stemp.f)

Function:

- Calculating heat conduction in soil.

Include files: Inclnum, prm_soil.

Variables:

- Z(0:NS+1): Real*8 Vertical grid in soil [m].
- TEXTURE(NX,NY,0:NS): Integer Soil type [1 to 24 USGS soil type].
- MYU: Real*8 Parameter for numerical scheme.
- DELT: Real*8 Time increment [s].
- ZENITH(NX,NY): Real*8 Solar zenith angle [deg.].
- RS(NX,NY): Real*8 Soil surface solar radiation flux [W m^{-2}].
- RSD(2,NX,NY): Real*8 Soil surface direct solar radiation flux [W m^{-2}].

- RSS(2,NX,NY): Real*8 Soil surface diffuse solar radiation flux [W m^{-2}].
- RL(NX,NY): Real*8 Soil surface long-wane radiation flux [W m^{-2}].
- TR(NX,NY): Real*8 Lowest atmosphere layer temperature [K].
- UR(NX,NY): Real*8 Lowest atmosphere layer wind speed [m s^{-1}].
- QR(NX,NY): Real*8 Lowest atmosphere layer humidity [kg kg^{-1}].
- CH0(NX,NY): Real*8 Heat exchange coefficient at soil surface.
- AIRDEN(NX,NY): Real*8 Air density [kg m^{-3}].
- PR0(NX,NY): Real*8 Precipitation intensity at soil surface [kg m^{-2} s^{-1}].
- TP(NX,NY): Real*8 Precipitation temperature [K].
- HTOPF(NX,NY): Real*8 Sensible heat flux at soil surface[W m^{-2}].
- HRADF(NX,NY): Real*8 Net radiation at soil surface [W m^{-2}].
- HTOPL(NX,NY): Real*8 Latent heat flux at soil surface [W m^{-2}].
- HGTOP(NX,NY): Real*8 Soil heat flux [W m^{-2}].
- HW(NX,NY,0:NS): Real*8 Soil water content [m^3 m^{-3}].
- EB(NX,NY,0:NS): Real*8 Evaporation rate of soil water [kg m^{-3} s^{-1}].
- T(NX,NY,0:NS): Real*8 Soil temperature [K].
- RES(NX,NY): Real*8 Soil surface water [kg m^{-2}].
- VFS(NX,NY,0:NS): Real*8 Vapor flux in soil [kg m^{-2} s^{-1}].
- ALBDD(2,NX,NY): Real*8 Soil surface albedo for direct solar radiation.
- ALBDS(2,NX,NY): Real*8 Soil surface albedo for diffuse solar radiation.
- EMIS(NX,NY): Real*8 Soil surface emissivity.

ESPARA (NX, NY, NS, TEXTURE, HW, T, RES, CSRS, KS, WORK) (espara.f)

Function:

- Calculating heat capacity and thermal conductivity of soil.

Include files: prm_soil.

Variables:

- NX: Integer Horizontal x-grid size.
- NY: Integer Horizontal y-grid size.
- NS: Integer Vertical grid size in soil.
- TEXTURE(NX,NY,0:NS): Integer Soil type [1 to 24 USGS soil type].
- HW(NX,NY,0:NS): Real*8 Soil water content [m^3 m^{-3}].
- T(NX,NY,0:NS): Real*8 Soil temperature [K].
- RES(NX,NY): Real*8 Soil surface water [kg m^{-2}].
- CSRS(NX,NY,0:NS): Real*8 Heat capacity of bulk soil [J m^{-3} K^{-1}].
- KS(NX,NY,NS): Real*8 Thermal conductivity of soil [m^2 s^{-1}].
- WORK(NX,NY,0:NS): Real*8 Thermal conductivity of soil [m^2 s^{-1}].

EALBED (NX, NY, NS, TEXTURE, HW, ZENITH, ALBDD, ALBDS, EMIS) (efalbedo.f)

Function:

- Calculating soil surface albedo and emissivity.

Include files: None.

Variables:

- NX:	Integer	Horizontal x-grid size.
- NY:	Integer	Horizontal y-grid size.
- NS:	Integer	Vertical grid size in soil.
- TEXTURE(NX,NY,0:NS):	Integer	Soil type [1 to 24 USGS soil type].
- HW(NX,NY,0:NS):	Real*8	Soil water content [m^3 m^{-3}].
- ZENITH(NX,NY):	Real*8	Solar zenith angle [deg.].
- ALBDD(2,NX,NY):	Real*8	Soil surface albedo for direct solar radiation.
- ALBDS(2,NX,NY):	Real*8	Soil surface albedo for diffuse solar radiation.
- EMIS(NX,NY):	Real*8	Soil surface emissivity.

SLCO2 (Z, TEXTURE, MYU, DELT, FRZ, SRZ, IFDBG, PHPS, TR, UR, QR, CE0, AIRDEN, PR0, HW, TS, QS, ET, EB, ER, RES, WF, CO2BOT, CO2R, SS0, SP0, AAZ, CO2S, FCO2S, ETCO2, SSCO2, RTCO2, ACO2G, ACO2A, DCO2A, FSCO2) (slco2.f)

Function:

- Calculating CO_2 transport in soil.

Include files: Inclnum.

Variables:

- Z(0:NS+1):	Real*8	Vertical grid in soil [m].
- TEXTURE(NX,NY,0:NS):	Integer	Soil type [1 to 24 USGS soil type].
- MYU:	Real*8	Parameter for numerical scheme.
- DELT:	Real*8	Time increment [s].
- FRZ(NX,NY,0:NS):	Real*8	Fractional root distribution [0 to 1 fraction].
- SRZ(NX,NY):	Real*8	Accumulated leaf area density (LAI) [m^2 m^{-2}].
- IFDBG	Integer	Debug output flag [1: on, 0: off].
- PHPS(NX,NY):	Real*8	Surface air pressure [hPa].
- TR(NX,NY):	Real*8	Lowest atmosphere layer temperature [K].
- UR(NX,NY):	Real*8	Lowest atmosphere layer wind speed [m s^{-1}].
- QR(NX,NY):	Real*8	Lowest atmosphere layer humidity [kg kg^{-1}].
- CE0(NX,NY):	Real*8	Vapor exchange coefficient at soil surface.
- AIRDEN(NX,NY):	Real*8	Air density [kg m^{-3}].
- PR0(NX,NY):	Real*8	Precipitation intensity at soil surface [kg m^{-2} s^{-1}].
- HW(NX,NY,0:NS):	Real*8	Soil water content [m^3 m^{-3}].

- TS(NX,NY,0:NS): Real*8 Soil temperature [K].
- QS(NX,NY,0:NS): Real*8 Specific humidity of soil pore [kg kg^{-1}].
- ET(NX,NY,0:NS): Real*8 Root uptake (transpiration) rate [kg m^{-3} s^{-1}].
- EB(NX,NY,0:NS): Real*8 Evaporation rate of soil water [kg m^{-3} s^{-1}].
- ER(NX,NY,0:NS): Real*8 Runoff [kg m^{-2} s^{-1}(surface), kg m^{-3} s^{-1}(in-soil)].
- RES(NX,NY): Real*8 Soil surface water [kg m^{-2}].
- WF(NX,NY,0:NS): Real*8 Water flux in soil [kg m^{-2} s^{-1}].
- CO2BOT(NX,NY): Real*8 Soil bottom CO_2 concentration [ppmv].
- CO2R(NX,NY): Real*8 Surface air CO_2 concentration [ppmv].
- SS0: Real*8 Optimal soil CO_2 production rate [μmol m^{-2} s^{-1}].
- SP0: Real*8 Optimal root CO_2 production rate [μmol m^{-2} s^{-1}].
- AAZ: Real*8 CO_2 production distribution parameter in the soil [m^{-1}].
- CO2S(NX,NY,0:NS): Real*8 Soil CO_2 concentration [ppmv].
- FCO2S(NX,NY,NS): Real*8 Soil CO_2 flux [ppmv m^{-2} s^{-1}].
- ETCO2(NX,NY,0:NS): Real*8 Root up-take CO_2 [ppmv s^{-1}].
- SSCO2(NX,NY,0:NS): Real*8 Soil respiration rate [ppmv s^{-1}].
- RTCO2(NX,NY,0:NS): Real*8 Root respiration rate [ppmv s^{-1}].
- ACO2G(NX,NY,0:NS): Real*8 Gas phase CO_2 concentration [ppmv].
- ACO2A(NX,NY,0:NS): Real*8 Aqueous phase CO_2 concentration [ppmv].
- DCO2A(NX,NY): Real*8 Drain rate of CO_2 [ppmv m s^{-1}].
- FSCO2(NX,NY): Real*8 Soil surface CO_2 flux [ppmv m s^{-1}].

HIFI1(QN, Q, QQ0, QQ1, WI, DELT, DZ) (shifi1.f)

Function:

- One-dimensional HIFI scheme[58] for advection term of CO_2 transport in soil.

Include files: Inclnum.

Variables:

- QN(NX,NY,0:NS): Real*8 Change in Q during DELT.
- Q(NX,NY,0:NS): Real*8 Dependent variable at the time step.
- QQ0(NX,NY): Real*8 Top boundary value of Q.
- QQ1(NX,NY): Real*8 Bottom boundary value of Q.
- WI(NX,NY,0:NS): Real*8 Advection velocity [m s^{-1}].
- DELT: Real*8 Time increment.
- DZ(0:NS): Real*8 Vertical grid [m].

RSCO2 (NX, NY, NS, NC, ZS, ZC, TEXTURE, RZ, AZ, PARABS, HW, PHPS, ROU, CHANGEE, VMAX25, SLOPE, UU, VV, TT, QQ, CO2, TC, ES, ET, ETCO2,

RS, AS, AF, AG, AP, IFDBG, TIMET) (svrsco2.f)

Function:

- Calculating CO_2 assimilation by photosynthesis and stomatal resistance.

Include files: None.

Variables:

- NX:	Integer	Horizontal x-grid size.
- NY:	Integer	Horizontal y-grid size.
- NS:	Integer	Vertical grid size in soil.
- NC:	Integer	Vertical grid size in vegetation canopy.
- ZS(0:NS+1):	Real*8	Vertical grid in soil [m].
- ZC(NX,NY,0:NC+1):	Real*8	3-D grid height in vegetation canopy [m].
- TEXTURE(NX,NY,0:NS):	Integer	Soil type [1 to 24 USGS soil type].
- RZ(NX,NY,0:NC,0:NS):	Real*8	Root distribution [0 to 1 fraction].
- AZ(NX,NY,0:NC):	Real*8	Leaf area density [m^2 m^{-3}].
- PARABS(2,NX,NY,NC):	Real*8	PAR absorbed by leaves [W m^{-2}].
- HW(NX,NY,0:NS):	Real*8	Soil water content [m^3 m^{-3}].
- PHPS(NX,NY):	Real*8	Surface air pressure [hPa].
- ROU(NX,NY):	Real*8	Air density [kg m^{-3}].
- CHANGEE(NX,NY,0:NC):	Real*8	Vapor exchange coefficient.
- VMAX25(NX,NY,0:NC):	Real*8	V_m at 25 °C [μmol m^{-2} s^{-1}].
- SLOPE(NX,NY,0:NC):	Real*8	Empirical constant m for stomatal resistance.
- UU(NX,NY,NC):	Real*8	Wind u-component [m s^{-1}].
- VV(NX,NY,NC):	Real*8	Wind v-component [m s^{-1}].
- TT(NX,NY,0:NC):	Real*8	Temperature of canopy air [°C].
- QQ(NX,NY,NC):	Real*8	Specific humidity of canopy air [kg kg^{-1}].
- CO2(NX,NY,NC):	Real*8	CO_2 concentration [ppmv].
- TC(2,NX,NY,0:NC):	Real*8	Temperature of sun-lit/shaded leaves [°C].
- ES(NX,NY,NC):	Real*8	Transpiration rate [kg m^{-2} s^{-1}].
- ET(NX,NY,0:NS):	Real*8	Root uptake (transpiration) rate [kg m^{-3} s^{-1}].
- ETCO2(NX,NY,0:NS):	Real*8	Root up-take CO_2 [μmol m^{-3} s^{-1} or ppmv s^{-1}].
- RS(2,NX,NY,0:NC):	Real*8	Stomatal resistance [s m^{-1}].
- AS(2,NX,NY,0:NC):	Real*8	Net CO_2 assimilation rate 1 [μmol m^{-2} s^{-1}].
- AF(2,NX,NY,0:NC):	Real*8	Total CO_2 flux from leaf [μmol m^{-2} s^{-1}].
- AG(2,NX,NY,0:NC):	Real*8	Gross CO_2 assimilation rate [μmol m^{-2} s^{-1}].
- AP(2,NX,NY,0:NC):	Real*8	Net CO_2 assimilation rate 2 [μmol m^{-2} s^{-1}].
- IFDBG	Integer	Debug output flag [1: on, 0: off].
- TIMET	Real*8	Integration time [h].

RESISTS (NX, NY, NS, NC, ZS, TEXTURE, RZ, RSSTMIN, PARCRT, SMX, DDN, SDN, HW, QA, TA, PHPS, RRF, PARABS, SUNABS, FLIT, RS, FMX, FTX) (svrsst.f)

Function:

- Calculating stomatal resistance by Jarvis-type scheme.

Include files: None.

Variables:

- NX:	Integer	Horizontal x-grid size.
- NY:	Integer	Horizontal y-grid size.
- NS:	Integer	Vertical grid size in soil.
- NC:	Integer	Vertical grid size in vegetation canopy.
- ZS(0:NS+1):	Real*8	Vertical grid in soil [m].
- TEXTURE(NX,NY,0:NS):	Integer	Soil type [1 to 24 USGS soil type].
- RZ(NX,NY,0:NC,0:NS):	Real*8	Root distribution [0 to 1 fraction].
- RSSTMIN(NX,NY,0:NC):	Real*8	Minimum stomatal resistance [s m^{-1}].
- PARCRT(NX,NY,0:NC):	Real*8	Critical value of PAR [W m^{-2}].
- SMX:	Real*8	Maximum solar radiation flux [W m^{-2}].
- DDN(2,NX,NY,0:NC):	Real*8	Downward direct solar radiation flux [W m^{-2}].
- SDN(2,NX,NY,0:NC):	Real*8	Downward diffuse solar radiation flux [W m^{-2}].
- HW(NX,NY,0:NS):	Real*8	Soil water content [m^3 m^{-3}].
- QA(NX,NY,NC):	Real*8	Specific humidity of canopy air [kg kg^{-1}].
- TA(NX,NY,0:NC):	Real*8	Temperature of canopy air [°C].
- PHPS(NX,NY):	Real*8	Surface air pressure [hPa].
- RRF(2,NX,NY,NC):	Real*8	Fraction of transpiration by sun-lit/shaded leaves.
- PARABS(2,NX,NY,NC):	Real*8	PAR absorbed by leaves [W m^{-2}].
- SUNABS(2,NX,NY,NC):	Real*8	Solar radiation absorbed by leaves [W m^{-2}].
- FLIT(NX,NY,NC):	Real*8	Fraction of sun-lit leaves [0 to 1 fraction].
- RS(2,NX,NY,0:NC):	Real*8	Stomatal resistance [s m^{-1}].
- FMX(2,NX,NY,0:NC):	Real*8	Stress function by humidity.
- FTX(2,NX,NY,0:NC):	Real*8	Stress function by temperature.

VLIQU (ZC, AZ, DELT, CHANGEE, WDSAT, WDEVP, FANGLE, FGRVEGE, ROU, PHPS, UUC, VVC, TTC, QQC, WLC, PRT, TP, RP, TC, WDL, RS, FLIT, PD, RRD, RRS, RRF, EPR, ECL, ECP, PR, WDLN, VEGTYPE) (svliqu.f)

Function:

- Calculating leaf surface water and water flux in canopy.

Include files: Inclnum.

Variables:

- ZC(NX,NY,0:NC+1):	Real*8	3-D grid height in vegetation canopy [m].
- AZ(NX,NY,0:NC):	Real*8	Leaf area density [m^2 m^{-3}].
- DELT:	Real*8	Time increment [s].
- CHANGEE(NX,NY,0:NC):	Real*8	Vapor exchange coefficient.
- WDSAT(NX,NY,0:NC):	Real*8	Maximum leaf surface water [kg m^{-2}].
- WDEVP(NX,NY,0:NC):	Real*8	Leaf surface water for max. evaporation [kg m^{-2}].
- FANGLE(NX,NY,0:NC):	Real*8	Mean zenith angle of leaf orientation [deg.].
- FGRVEGE(NX,NY,0:NC):	Real*8	Green leaf fraction [0 to 1 fraction].
- ROU(NX,NY):	Real*8	Air density [kg m^{-3}].
- PHPS(NX,NY):	Real*8	Surface air pressure [hPa].
- UUC(NX,NY,NC):	Real*8	Wind u-component [m s^{-1}].
- VVC(NX,NY,NC):	Real*8	Wind v-component [m s^{-1}].
- TTC(NX,NY,0:NC):	Real*8	Temperature of canopy air [°C].
- QQC(NX,NY,NC):	Real*8	Specific humidity of canopy air [kg kg^{-1}].
- WLC(NX,NY,NC):	Real*8	Fog water in canopy air [kg kg^{-1}].
- PRT(NX,NY):	Real*8	Precipitation intensity [kg m^{-2} s^{-1}].
- TP(NX,NY):	Real*8	Precipitation temperature [K].
- RP(NX,NY):	Real*8	Radius of rain drop [m].
- TC(2,NX,NY,0:NC):	Real*8	Temperature of sun-lit/shaded leaves [°C].
- WDL(NX,NY,0:NC):	Real*8	Leaf surface water [kg m^{-2}].
- RS(2,NX,NY,0:NC):	Real*8	Stomatal resistance [s m^{-1}].
- FLIT(NX,NY,NC):	Real*8	Fraction of sun-lit leaves [0 to 1 fraction].
- PD(NX,NY,NC):	Real*8	Drip from leaf surface water [kg m^{-2} s^{-1}].
- RRD(2,NX,NY,NC):	Real*8	Total conductance for transpiration [m s^{-1}].
- RRS(2,NX,NY,NC):	Real*8	Total conductance for evaporation [m s^{-1}].
- RRF(2,NX,NY,NC):	Real*8	Fraction of transpiration by sun-lit/shaded leaves.
- EPR(NX,NY,NC):	Real*8	Evaporation from precipitation [kg m^{-3} s^{-1}].
- ECL(NX,NY,NC):	Real*8	Accretion of fog by precipitation [kg m^{-3} s^{-1}].
- ECP(NX,NY,NC):	Real*8	Accretion of fog by leaf [kg m^{-2} s^{-1}].
- PR(NX,NY,0:NC):	Real*8	Vertical water flux in canopy [kg m^{-2} s^{-1}].
- WDLN(NX,NY,0:NC):	Real*8	Leaf surface water for next time step [kg m^{-2}].
- VEGTYPE(NX,NY,0:NC):	Integer	Vegetation type in zvege.table_1D.

FOGCAP (NL, DELT, FRW, ROU, WS, WL, ECP, ECL, FRV, VTYPE, AZ) (svfogcp.f)

Function:

- Calculating cloud water collection rate by leaves.

Include files: Inclcon2, prm_fog.

Variables:

- NL:	Integer	Canopy layer number.
- DELT:	Real*8	Time increment [s].
- FRW:	Real*8	the product of projection coefficient for vertical direction and horizontal wind speed [m s^{-1}].
- ROU:	Real*8	Air density [kg m^{-3}].
- WS:	Real*8	Wind speed at the layer of NL [m s^{-1}].
- WL:	Real*8	Liquid water in canopy air at the layer of NL [kg m^{-3}].
- ECP:	Real*8	Accretion of fog by leaf at the layer of NL [kg m^{-2} s^{-1}].
- ECL:	Real*8	Accretion of fog by precipitation at the layer of NL [kg m^{-3} s^{-1}].
- FRV:	Real*8	Projection coefficient for vertical direction.
- VTYPE:	Integer	Vegetation type in zvege.table_1D at the layer of NL.
- AZ:	Real*8	Leaf area density at the layer of NL [m^2 m^{-3}].

VTEMP (ZC, AZ, DELT, CHANGEH, FANGLE, REFLECT, TRANSMT, EMISSIV, ROU, PHPS, UUC, VVC, TTC, QQC, WLC, PR, TP, RDDN, RSDN, RSUP, RLDN, RLUP, RRD, RRS, ED, ES, WDL, ZENITH, FLIT, TET, HS, HC, TC, ESL, ESS, ASCO2, EAS, RES) (svtemp.f)

Function:

- Calculating leaf surface heat budget.

Include files: Inclnum.

Variables:

- ZC(NX,NY,0:NC+1):	Real*8	3-D grid height in vegetation canopy [m].
- AZ(NX,NY,0:NC):	Real*8	Leaf area density [m^2 m^{-3}].
- DELT:	Real*8	Time increment [s].
- CHANGEH(NX,NY,0:NC):	Real*8	Heat exchange coefficient.
- FANGLE(NX,NY,0:NC):	Real*8	Mean zenith angle of leaf orientation [deg.].
- REFLECT(2,NX,NY,0:NC):	Real*8	Leaf reflectivity for visible and near-infrared.
- TRANSMT(2,NX,NY,0:NC):	Real*8	Leaf transmissivity for visible and near-infrared.
- EMISSIV(NX,NY,0:NC):	Real*8	Leaf emissivity.
- ROU(NX,NY):	Real*8	Air density [kg m^{-3}].
- PHPS(NX,NY):	Real*8	Surface air pressure [hPa].
- UUC(NX,NY,NC):	Real*8	Wind u-component [m s^{-1}].
- VVC(NX,NY,NC):	Real*8	Wind v-component [m s^{-1}].

- TTC(NX,NY,0:NC): Real*8 Temperature of canopy air [°C].
- QQC(NX,NY,NC): Real*8 Specific humidity of canopy air [kg kg^{-1}].
- WLC(NX,NY,NC): Real*8 Fog water in canopy air [kg kg^{-1}].
- PR(NX,NY,0:NC): Real*8 Vertical water flux in canopy [kg m^{-2} s^{-1}].
- TP(NX,NY): Real*8 Precipitation temperature [K].
- RDDN(2,NX,NY,0:NC): Real*8 Downward direct solar radiation flux [W m^{-2}].
- RSDN(2,NX,NY,0:NC): Real*8 Downward diffuse solar radiation flux [W m^{-2}].
- RSUP(2,NX,NY,0:NC): Real*8 Upward diffuse solar radiation flux [W m^{-2}].
- RLDN(2,NX,NY,0:NC): Real*8 Downward long-wave radiation flux [W m^{-2}].
- RLUP(2,NX,NY,0:NC): Real*8 Upward long-wave radiation flux [W m^{-2}].
- RRD(2,NX,NY,NC): Real*8 Total conductance for transpiration [m s^{-1}].
- RRS(2,NX,NY,NC): Real*8 Total conductance for evaporation [m s^{-1}].
- ED(NX,NY,NC): Real*8 Evaporation rate of leaf surface water [kgm^{-2} s^{-1}].
- ES(NX,NY,NC): Real*8 Transpiration rate [kg m^{-2} s^{-1}].
- WDL(NX,NY,0:NC): Real*8 Leaf surface water [kg m^{-2}].
- ZENITH(NX,NY): Real*8 Solar zenith angle [deg.].
- FLIT(NX,NY,NC): Real*8 Fraction of sun-lit leaves [0 to 1 fraction].
- TET(NX,NY,0:NC): Real*8 Temperature of root up-take water [K].
- HS(NX,NY,0:NC): Real*8 Cooling by precipitation [W m^{-2}].
- HC(NX,NY,0:NC): Real*8 Heat exchange between leaf and air [W m^{-2}].
- TC(2,NX,NY,0:NC): Real*8 Temperature of sun-lit/shaded leaves [°C].
- ESL(NX,NY,NC): Real*8 Transpiration of sun-lit leaves [kg m^{-2} s^{-1}].
- ESS(NX,NY,NC): Real*8 Transpiration of sun-shaded leaves [kg m^{-2} s^{-1}].
- ASCO2(2,NX,NY,0:NC): Real*8 Net CO_2 assimilation rate [μmol m^{-2} s^{-1}].
- EAS(NX,NY,0:NC): Real*8 Energy consumption by photosynthesis [W m^{-2}].
- RES(NX,NY): Real*8 Soil surface water [kg m^{-2}].

GENER (I1, J1, ID, DK, A) (pgener.f)

Function:

- Setting variables of numerical scheme for diffusion equation in atmosphere.

Include files: Inclnum and Inclcon1.

Variables:

- I1: Integer Horizontal x-grid number.
- J1: Integer Horizontal y-grid number.
- ID: Integer Grid type.
- DK(M1): Real*8 Diffusivity K in (7-1).
- A(N1): Real*8 Coefficient A in (7-1).

DIREC2 (N, TOP, PE1, PF1, Q) (pgener.f)

Function:

- Numerical scheme for diffusion equation in atmosphere with variable top boundary.

Include files: Inclnum, Inclcon1.

Variables:

- N:	Integer	Vertical grid size.
- TOP:	Real*8	Gradient of variable at the top boundary.
- PE1:	Real*8	Surface boundary condition.
- PF1:	Real*8	Surface boundary condition.
- Q(M1):	Real*8	Solution.

DIREC1 (N, TOP, PE1, PF1, Q) (pgener.f)

Function:

- Numerical scheme for diffusion equation in atmosphere with constant top boundary.

Include files: Inclnum, Inclcon1.

Variables:

- N:	Integer	Vertical grid size.
- TOP:	Real*8	Gradient of variable at the top boundary.
- PE1:	Real*8	Surface boundary condition.
- PF1:	Real*8	Surface boundary condition.
- Q(M1):	Real*8	Solution.

SED (NL, ROU, WL, SEDWL) (svsed.f)

Function:

- Calculating gravitational flux of cloud water.

Include files: Inclcon2, prm_fog.

Variables:

- NL:	Integer	Atmospheric layer number.
- ROU:	Real*8	Air density [kg m^{-3}].
- WL:	Real*8	Liquid water in canopy air at the layer of NL [kg m^{-3}].
- SEDWL:	Real*8	Gravitational flux of cloud water [kg m^{-2} s^{-1}].

ELI2VA(TA, QA, PHPA, RO, CP, CL, QASS, EFDT) (eli2va.f)

Function:

- Calculating temperature and specific humidity after evaporation.

Include files: None.

Variables:

- TA:	Real*8	Air temperature before evaporation [K].
- QA :	Real*8	Specific humidity before evaporation [kg kg^{-1}].
- PHPA:	Real*8	Air pressure [hPa].
- RO:	Real*8	Air density [kg m^{-3}].
- CP:	Real*8	Specific heat of air [J K^{-1} kg^{-1}].
- CL:	Real*8	Latent heat of vaporization [J kg^{-1}].
- QASS:	Real*8	Saturated specific humidity [kg kg^{-1}].
- EFDT:	Real*8	Potential evaporation [kg m^{-3}].

A-4 Functions

SHMD (TEMP, PRESSURE, JFLG) (faipsy.f)

Input:	- TEMP:	Real*8	Temperature [K].
	- PRESSURE:	Real*8	Air pressure [hPa].
	- JFLG:	Integer	Flag [1: liquid water, 2: ice].
Output:	- SHMD:	Real*8	Saturated specific humidity [kg kg^{-1}].

PSYM (Z, STB, ZZER) (faipsy.f)

Input:	- Z:	Real*8	Height [m].
	- STB:	Real*8	Stability length scale [m].
	- ZZER:	Real*8	Roughness height of wind [m].
Output:	- PSYM:	Real*8	Integrated shear function of wind.

PSYH (Z, STB, ZZER) (faipsy.f)

Input:	- Z:	Real*8	Height [m].
	- STB:	Real*8	Stability length scale [m].
	- ZZER:	Real*8	Roughness height of heat [m].
Output:	- PSYH:	Real*8	Integrated shear function of temperature.

FL (T) (fl.f)

Input:	- T:	Real*8	Temperature [K].
Output:	- FL:	Real*8	Latent heat of vaporization [J kg^{-1}].

FCPAIR (Q) (fcpair.f)

Input:	- Q:	Real*8	Specific humidity [kg kg^{-1}].
Output:	- FCPAIR:	Real*8	Specific heat of air [J kg^{-1} K^{-1}].

FDENSA (D, Q, T, QQ, TT) (fdensa.f)

Input:	- D:	Real*8	Air density [kg m^{-3}].
	- Q:	Real*8	Specific humidity of air [kg kg^{-1}].
	- T:	Real*8	Air temperature [K].
	- QQ:	Real*8	Specific humidity of soil pore [kg kg^{-1}].
	- TT:	Real*8	Soil temperature [K].
Output:	- FDENSA:	Real*8	Density of soil pore air [kg m^{-3}].

FCW (T) (fcw.f)

Input:	- T:	Real*8	Temperature [K].
Output:	- FCPAIR:	Real*8	Specific heat of water [J kg^{-1} K^{-1}].

POTEV (T, BG, GA, QR, BRN, DLT, QSAT) (swadsp.f)

Input:	- T:	Real*8	Temperature [K].
	- BG:	Real*8	Soil heat flux at soil surface [W m^{-2}].
	- GA:	Real*8	Transfer coefficient for sensible heat flux at soil surface.
	- QR:	Real*8	Specific humidity of air [kg kg^{-1}].
	- BRN:	Real*8	Net radiation at soil surface [W m^{-2}].
	- DLT:	Real*8	Coefficient for potential evaporation calculation.
	- QSAT:	Real*8	Saturated specific humidity [kg kg^{-1}].
Output:	- POTEV:	Real*8	Potential evaporation at soil surface [kg m^{-2} s^{-1}].

EPS (DP, WS, VTYPE) (feps.f)

Input:	- DP:	Real*8	Droplet diameter of cloud water [m].
	- WS:	Real*8	Wind speed [m s^{-1}].
Output:	- EPS:	Real*8	Capture efficiency of cloud water droplets.

FDIST (DDP, WL) (feps.f)

Input:	- DDP:	Real*8	Droplet diameter of cloud water [m].
	- WL:	Real*8	Liquid water in canopy air [kg kg^{-1}].
Output:	- FDIST:	Real*8	Probability density of cloud water droplet.

DGL10 (a, b, AD, BD, PD, QD) (feps.f)

Input:	- a:	Real*8	Constant for Gauss-Legendre integration.
	- b:	Real*8	Constant for Gauss-Legendre integration.
	- AD:	Real*8	Constant in Deirmendjian's function.

	- BD:	Real*8	Constant in Deirmendjian's function.
	- PD:	Real*8	Constant in Deirmendjian's function.
	- QD:	Real*8	Constant in Deirmendjian's function.
Output:	- DGL10:	Real*8	Integrated value of probability density of cloud water droplet.

DEIR (DP, AD, BD, PD, QD) (feps.f)

Input:	- DP:	Real*8	Mean droplet diameter of cloud water [m].
	- AD:	Real*8	Constant in Deirmendjian's function.
	- BD:	Real*8	Constant in Deirmendjian's function.
	- PD:	Real*8	Constant in Deirmendjian's function.
	- QD:	Real*8	Constant in Deirmendjian's function.
Output:	- DEIR:	Real*8	Probability density of cloud water droplet for Deirmendjian parameterization.

VGRV (X) (svfopcp.f, svsed.f)

Input:	- X:	Real*8	Droplet diameter [m].
Output:	- VGRV:	Real*8	Terminal settling velocity of cloud droplet [m s^{-1}].

SHMDD (TEMP, PRESSURE, JFLG) (faipsy.f)

Input:	- TEMP:	Real*8	Temperature [K].
	- PRESSURE:	Real*8	Air pressure [hPa].
	- JFLG:	Integer	Flag [1: liquid water, 2: ice].
Output:	- SHMDD:	Real*8	Derivative of saturated humidity [kg kg^{-1} K^{-1}].

FAIM (Z, STB) (faipsy.f)

Input:	- Z:	Real*8	Height [m].
	- STB:	Real*8	Stability length scale [m].
Output:	- FAIM:	Real*8	Non-dimensional shear function of wind.

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度 (a)，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立法メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率 (b)	（数字の） 1	1
比透磁率 (b)	（数字の） 1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(b)	rad	1 (b)	m/m
立体角	ステラジアン(b)	sr(c)	1 (b)	m^2/m^2
周波数	ヘルツ (d)	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度(e)	℃		K
光束	ルーメン	lm	cd sr(c)	cd
照度	ルクス	lx	lm/m^2	m^{-2} cd
放射性核種の放射能 (f)	ベクレル (d)	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト (g)	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		s^{-1} mol

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	m^{-3} sA
表面電荷	クーロン毎平方メートル	C/m^2	m^{-2} sA
電束密度，電気変位	クーロン毎平方メートル	C/m^2	m^{-2} sA
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（X線及びγ線）	クーロン毎キログラム	C/kg	kg^{-1} sA
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}$ mol

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^9	ギガ	G	10^{-12}	ピコ	p
10^6	メガ	M	10^{-15}	フェムト	f
10^3	キロ	k	10^{-18}	アト	a
10^2	ヘクト	h	10^{-21}	ゼプト	z
10^1	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10800) rad
秒	”	1”=(1/60)’=(π/648000) rad
ヘクタール	ha	$1ha=1hm^2=10^4m^2$
リットル	L，l	$1L=1l=1dm^3=10^3cm^3=10^{-3}m^3$
トン	t	$1t=10^3$ kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	$1eV=1.602\ 176\ 53(14)\times10^{-19}J$
ダルトン	Da	$1Da=1.660\ 538\ 86(28)\times10^{-27}kg$
統一原子質量単位	u	1u=1 Da
天文単位	ua	$1ua=1.495\ 978\ 706\ 91(6)\times10^{11}m$

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	$1\ bar=0.1MPa=100kPa=10^5Pa$
水銀柱ミリメートル	mmHg	1mmHg=133.322Pa
オングストローム	Å	$1\ Å=0.1nm=100pm=10^{-10}m$
海里	M	1 M=1852m
バーン	b	$1\ b=100fm^2=(10^{-12}cm)2=10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デジベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	$1\ erg=10^{-7}$ J
ダイン	dyn	$1\ dyn=10^{-5}N$
ポアズ	P	$1\ P=1\ dyn\ s\ cm^{-2}=0.1Pa\ s$
ストークス	St	$1\ St\ =1cm^2\ s^{-1}=10^{-4}m^2\ s^{-1}$
スチルブ	sb	$1\ sb\ =1cd\ cm^{-2}=10^4cd\ m^{-2}$
フォト	ph	$1\ ph=1cd\ sr\ cm^{-2}\ 10^4lx$
ガル	Gal	$1\ Gal\ =1cm\ s^{-2}=10^{-2}ms^{-2}$
マクスウェル	Mx	$1\ Mx = 1G\ cm^2=10^{-8}Wb$
ガウス	G	$1\ G\ =1Mx\ cm^{-2}\ =10^{-4}T$
エルステッド (c)	Oe	$1\ Oe\ ≙\ (10^3/4π)A\ m^{-1}$

(c) ３元系のCGS単位系とSIでは直接比較できないため、等号「≙」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	$1\ Ci=3.7\times10^{10}Bq$
レントゲン	R	$1\ R = 2.58\times10^{-4}C/kg$
ラド	rad	$1\ rad=1cGy=10^{-2}Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2}Sv$
ガンマ	γ	1 γ =1 nT=10-9T
フェルミ		1フェルミ=1 fm=10-15m
メートル系カラット		1メートル系カラット = 200 mg = 2×10-4kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー）4.184J（「熱化学」カロリー）
ミクロン	µ	$1\ µ\ =1µm=10^{-6}m$

（第8版，2006年改訂）