JAERI-Data/Code
2004-014

ATMOSPHERE-SOIL-VEGETATION MODEL INCLUDING CO_2 EXCHANGE PROCESSES : SOLVEG2

November 2004

Haruyasu NAGAI

日 本 原 子 力 研 究 所
Japan Atomic Energy Research Institute

編集兼発行　日本原子力研究所

Atmosphere-soil-vegetation Model Including CO_2 Exchange Processes: SOLVEG2

Haruyasu NAGAI

Department of Environmental Sciences
Tokai Research Establishment
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken

(Received September 17, 2004)

A new atmosphere-soil-vegetation model named SOLVEG2 (SOLVEG version 2) was developed to study the heat, water, and CO_2 exchanges between the atmosphere and land-surface. The model consists of one-dimensional multilayer sub-models for the atmosphere, soil, and vegetation. It also includes sophisticated processes for solar and long-wave radiation transmission in vegetation canopy and CO_2 exchanges among the atmosphere, soil, and vegetation. Although the model usually simulates only vertical variation of variables in the surface-layer atmosphere, soil, and vegetation canopy by using meteorological data as top boundary conditions, it can be used by coupling with a three-dimensional atmosphere model. In this paper, details of SOLVEG2, which includes the function of coupling with atmosphere model MM5, are described.

Keywords: Land-surface Model, SOLVEG2, Atmosphere, Soil, Vegetation, CO_2

CO_2 交換過程を含む大気‐土壌‐植生モデル：SOLVEG2

日本原子力研究所東海研究所環境科学研究部
永井　晴康

（2004 年　9 月 17 日受理）

大気と陸面間の熱、水及び CO_2 交換を研究するために、新しい大気‐土壌‐植生モデル SOLVEG2（SOLVEG　バージョン2）の開発を行った。モデルは、大気、土壌、植生それぞれについての 1 次元多層サブモデルからなる。また、モデルは、植生層内の日射及び長波放射の伝達、及び大気、土壌、植生間の CO_2 交換を計算する精緻な過程も含んでいる。本モデルは、通常の使用では気象データを上部境界条件として接地層大気、土壌及び植生層変数の鉛直分布を計算するだけであるが、3 次元の大気モデルと結合して計算を行う機能も有する。本報告は、大気モデル　MM5　との結合機能も含めて、SOLVEG2　の詳細を記述する。

東海研究所：〒319－1195　茨城県那珂郡東海村白方白根2－4

Contents

目　次

1. Introduction

The heat, water, and CO_2 exchanges between the atmosphere and land surface is important for environmental studies such as the prediction of climate change, but is not well understood. It is a big challenge for modeling and clarifying these exchanges among the atmosphere, soil, and vegetation and for predicting the impacts of climate change on the land surface exchange processes for heat, water, and CO_2. It is also related strongly to the dry and wet depositions of material such as air pollutions to the soil and vegetation, since the vegetation physiology, such as the transpiration, respiration, and photosynthetic CO_2 assimilation, affects the material exchange in the atmosphere, soil, and vegetation system.

An atmosphere-soil-vegetation model named SOLVEG was developed[1), 2)] to study the heat and water exchanges at the ground surface. The characteristic feature of the model is that it is multilayered and so may resolve realistically processes of the heat and water exchanges in each layer of the atmosphere-soil-vegetation system. It also includes the sophisticated radiation processes for transmission of the solar and long-wave radiation fluxes in the canopy. Thus, the model avoids uncertain parameterizations as far as possible. The framework of the model is unique which combines two types of model concepts. One is something like bulk method, which has been used mainly in atmospheric models to provide exchange process between the atmosphere and plant or soil as a whole[3), 4), 5), 6), 7), 8), 9)]. The other is the research model, which uses the multilayer expression for the vegetation canopy to examine the turbulence transfer of momentum, heat, and moisture within and above the canopy[10), 11), 12), 13), 14), 15)]. The former types of models use a single or two-layer expression for the vegetation canopy. In order to remove uncertainties in parameterizations and assumptions for the canopy in the SOLVEG, the in-canopy processes are explicitly calculated in the similar way to the latter types of models.

For this model framework for the heat and water exchanges, performance tests have been carried out[16), 17)] using observed data in the Cooperative Atmosphere-Surface Exchange Study (CASES) [18)]. These tests demonstrated the validity and applicability of the new model's framework with the multilayer expression of the vegetation and soil and of the comprehensive processes included. In addition, impacts of detailed calculation of the canopy radiation transmission and the stomatal resistance on the heat and water exchanges in the canopy were also tested[17)]. It proved the necessity of treating the sun-lit and shaded leaves separately to get accurate prediction of the stomatal resistance, similar to the result of other study[19)]. The comparison with other models, OSU-LSM[9)] and NCAR-LSM[20)], is also carried out[21), 22)], and SOLVEG showed comparable performance to the other models or better in some cases.

Besides the heat, water, momentum, and radiation exchanges between the atmosphere and land surface, the CO_2 exchange processes are incorporated into SOLVEG[23)]. The sophisticated radiation process[17)] can provide the photosynthetically active radiation (PAR) flux at each layer in the canopy, which is necessary for the calculation of photosynthetic CO_2 assimilation.

The model also considers interactions between the CO_2 exchange and other exchanges by using the stomatal resistance scheme based on the photosynthesis. Since the leaf photosynthesis determines the stomatal resistance that is the key factor for the heat and water exchanges between the atmosphere and vegetation, the CO_2 exchange affects the heat and water exchanges through the photosynthesis. It has been done to consider this interaction in some land surface models[20), 24), 25)], and the effectiveness of these schemes is discussed[26)]. However, it has not been done in multilayer models by explicitly calculating all related exchanges (heat, water, momentum, radiation, and CO_2). This new model framework was also tested[23)] by using measured data. The new version of the model is named SOLVEG2.

Although the model usually simulates only vertical variation of variables in the surface-layer atmosphere, soil, and vegetation canopy by using meteorological data as top boundary conditions, it can be used by coupling with a three-dimensional atmosphere model. For coupling with the atmosphere model, one-dimensional model variables are expanded to three-dimensional ones whose horizontal coordinates coincide with those of atmosphere model. However, no interactions in horizontal directions are considered in the model. A non-hydrostatic atmospheric dynamic model of Pennsylvania State University and National Center for Atmospheric Research (PSU/NCAR-MM5)[27)] is used for this coupling, and a unique method is applied to combine the models. The method uses the function called MPMD (Multiple Program Multiple Data) of the parallel programming library MPI (Message Passing Interface), which allows parallel computers to run a parallel program with different executables. The atmosphere model MM5 and SOLVEG2 are coupled by exchanging calculation results by using MPI on their independent parallel calculations. The modifications of models for this coupling are easy, simply adding some modules for data exchanges to each model code without changing each model's original structure. This feature is helpful to make a model code coupling with a community model like MM5, which is updated regularly. Moreover, this coupling method is flexible and allows the use of independent time step and grid interval for each model.

In this paper, details of SOLVEG2, which includes the function of coupling with atmosphere model MM5, are described.

2. Model Overview

The model consists of one-dimensional multilayer sub-models for the atmosphere, soil, and vegetation, and a radiation scheme calculating the transmission of solar and long-wave radiation fluxes in the canopy layer. The CO_2 exchange processes are included in each sub-model. The model simulates diurnal variation and seasonal changes of variables in the surface-layer atmosphere, soil, and vegetation canopy, and exchanges of energy and water among these systems, by using meteorological data of the surface-layer atmosphere as top boundary conditions. The modeled processes are schematically illustrated in Fig. 2-1. An overview of the model and only basic equations are described here, and details of each sub-model are given in the following chapters.

The atmosphere sub-model calculates atmospheric variables by numerically solving one-dimensional diffusion equations for the horizontal wind speed components u and v [m s^{-1}], potential temperature θ [K], specific humidity q_a [kg kg^{-1}], fog water content w_f [kg kg^{-1}], turbulence kinetic energy e [m^2 s^{-2}], turbulence length scale λ [m], and CO_2 concentration c_{co2} [ppmv]. By using φ for these variables, one-dimensional diffusion equations are described in the same form as

$$\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial z} K_z \frac{\partial \phi}{\partial z} + F_\phi, \qquad (2\text{-}1)$$

where K_z [m^2 s^{-1}] is the vertical turbulence diffusivity calculated by the turbulence closure model[28]. The last term F_φ is a forcing term, and exchanges between the vegetation and canopy air are considered in this term as the volume source/sink of momentum, heat, water in liquid and gas phases, turbulence energy, and CO_2. The expression of this term for each variable is presented in the following chapter. The top boundary conditions are given as input data, and the soil surface boundary conditions are the momentum, heat, water vapor, and CO_2 fluxes calculated by using the soil surface temperature, specific humidity, and CO_2 concentration determined by the soil sub-model.

The soil sub-model calculates the soil temperature T_s [K], volumetric soil water content η_w [m^3 m^{-3}], specific humidity of air in soil pore space q_s [kg kg^{-1}], and CO_2 concentration in gas phase c_{sg} [ppmv] by the heat conduction equation, Richards equation[29], diffusion equation, and CO_2 conservation equation[30), 31)], respectively, as

$$\frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z} K_T \frac{\partial T_s}{\partial z} - \frac{l E_b}{C_s \rho_s} - \frac{C_w E_w}{C_s \rho_s} \frac{\partial T_s}{\partial z}, \qquad (2\text{-}2)$$

$$\frac{\partial \eta_w}{\partial t} = -\frac{1}{\rho_w} \left(\frac{\partial E_w}{\partial z} + E_t + E_b \right), \qquad (2\text{-}3)$$

$$\frac{\partial [(\eta_{ws} - \eta_w) q_s]}{\partial t} = \frac{\partial}{\partial z} D_w f_a(\eta_w) \frac{\partial q_s}{\partial z} + \frac{E_b}{\rho}, \qquad (2\text{-}4)$$

and $$\frac{\partial}{\partial t}V_E c_{sg} = \frac{\partial}{\partial z}D_E\frac{\partial c_{sg}}{\partial z} - \frac{\partial}{\partial z}E_E^* c_{sg} - E_t^* K_H R T_s c_{sg} + S_{CO2},\qquad (2\text{-}5)$$

where K_T [m^2 s^{-1}], l [J kg^{-1}], D_w [m^2 s^{-1}], and η_{ws} [m^3 m^{-3}] are the thermal conductivity of soil, latent heat of vaporization, molecular diffusivity for water vapor in air, and saturated volumetric soil water content, respectively, ρ, ρ_s, and ρ_w [kg m^{-3}] are the densities of air, bulk soil, and water, respectively, C_s and C_w [J m^{-3} K^{-1}] are the volumetric heat capacities of bulk soil and water, respectively, $f(\eta_w)$ is the coefficient for distortion of pore (tortuosity), V_E [m^3 m^{-3}], D_E [m^2 s^{-1}], and E_E^* [m^3 m^{-2} s^{-1}] are the volume of media, diffusivity, and advection velocity of CO_2 considering both gas and aqueous phases, E_t^* [m^3 m^{-2} s^{-1}] is the volumetric root uptake rate, K_H [mol m^{-3} Pa^{-1}] is Henry's constant, and S_{CO2} [ppmv s^{-1}] is CO_2 production term. Equations for heat, water, and specific humidity are closely related through the phase change of water (evaporation rate E_b [kg m^{-3} s^{-1}]). The liquid water flux E_w [kg m^{-2} s^{-1}] also transports the heat as the last term on the right hand side of (2-2). The second term E_t [kg m^{-3} s^{-1}] on the right hand side of (2-3) represents the root uptake rate of soil water, which is the transpiration rate determined in the vegetation sub-model. The soil sub-model is coupled with the atmosphere sub-model to satisfy the soil surface heat, water, and CO_2 budgets. Details of these terms and surface heat and water budget calculations are presented later in the chapter of soil sub-model.

The vegetation sub-model calculates the leaf temperature T_c [K], leaf surface water w_d [kg m^{-2}], and CO_2 assimilation rate A_n [μmol m^{-2} s^{-1}] at each canopy layer, and vertical liquid water flux in the canopy P_r [kg m^{-2} s^{-1}]. The leaf temperature is calculated by solving a leaf surface heat budget equation,

$$R_c = H_c + l(E_d + E_s) + H_p,\qquad (2\text{-}6)$$

where R$_c$, H_c [J m^{-2} s^{-1}], E_d, E_s [kg m^{-2} s^{-1}], and H_p [J m^{-2} s^{-1}] are the net radiation, sensible heat flux, evaporation rate of leaf surface water, transpiration rate, and cooling by precipitation, respectively, and each term is determined by the leaf temperature and variables by the atmosphere sub-model and the radiation scheme. The CO_2 assimilation rate is calculated by formulations[32], expressed as

$$A_n = \min(w_c, w_e, w_s) - R_d,\qquad (2\text{-}7)$$

where , w_c [μmol m^{-2} s^{-1}], w_e [μmol m^{-2} s^{-1}], and w_s [μmol m^{-2} s^{-1}] are the limitation by efficiency of the photosynthetic enzyme system (Rubisco), limitation by absorbed PAR, and limitation by the capacity of leaf to export the products of photosynthesis, and R_d [μmol m^{-2} s^{-1}] is the leaf respiration rate. This variable determines the stomatal resistance r_s^* [m^2 s μmol^{-1}], which is important for transpiration calculation, by using the empirical relationship[33),34)]. The other variables are determined by equations,

$$\frac{dw_d}{dt} = E_{\text{int}} - E_d + E_{cap} - P_d, \tag{2-8}$$

and
$$\frac{dP_r}{dz} = a(E_{\text{int}} - P_d) + E_{pr} - E_{col}, \tag{2-9}$$

where a [m^2 m^{-3}] is the leaf area density, terms E_{int}, E_{cap} [kg m^{-2} s^{-1}], E_{pr}, and E_{col} [kg m^{-3} s^{-1}] are the water exchanges due to interception of precipitation by leaves, capture of fog water by leaves, evaporation of rain droplets, and capture of fog water by rain droplets, respectively, and P_d [kg m^{-2} s^{-1}] is the drip from leaves. For P_r, the input precipitation intensity becomes the boundary value at the canopy top, and a calculated value at the canopy bottom is provided for the surface water budget calculation in the soil sub-model.

The radiation scheme calculates the downward and upward fluxes of the solar radiation and long-wave radiation in the canopy, and provides the radiation energy input for heat budget calculations at the soil surface and canopy layers. It was modified to treat the direct and diffuse radiation fluxes separately[17]. The transmission equations for the downward direct solar radiation flux $S_d^\downarrow$ [W m^{-2}], downward and upward diffuse solar radiation fluxes $S_s^\downarrow$ and $S_s^\uparrow$ [W m^{-2}], and downward and upward long-wave radiation fluxes $L^\downarrow$ and $L^\uparrow$ [W m^{-2}] are expressed as

$$\frac{dS_d^\downarrow}{dz} = (aF_{rd} + a'_w + A'_w)S_d^\downarrow, \tag{2-10}$$

$$\frac{dS_s^\downarrow}{dz} = \left[aF_{rs}(1 - f_{sf}) + a'_w + A'_w\right]S_s^\downarrow - (aF_{rs}f_{sb} + A'_w)S_s^\uparrow - aF_{rd}f_{df}S_d^\downarrow, \tag{2-11}$$

$$\frac{dS_s^\uparrow}{dz} = -\left[aF_{rs}(1 - f_{sf}) + a'_w + A'_w\right]S_s^\uparrow + (aF_{rs}f_{sb} + A'_w)S_s^\downarrow + aF_{rd}f_{db}S_d^\downarrow, \tag{2-12}$$

$$\frac{dL^\downarrow}{dz} = aF_{rs}\left[(1 - f_{sf})L^\downarrow - f_{sb}L^\uparrow - \varepsilon_c\sigma T_c^4\right] + k_l w_l\left(L^\downarrow - \sigma T_a^4\right), \tag{2-13}$$

and
$$\frac{dL^\uparrow}{dz} = -aF_{rs}\left[(1 - f_{sf})L^\uparrow - f_{sb}L^\downarrow - \varepsilon_c\sigma T_c^4\right] - k_l w_l\left(L^\uparrow - \sigma T_a^4\right), \tag{2-14}$$

where a [m^2 m^{-3}] is the leaf area density, f_{db}, f_{df}, f_{sb}, and f_{sf} are the scattering coefficients, a'_w ($= a_w/\delta z$) and A'_w ($= A_w/\delta z$) are the absorptivity and reflectivity of liquid water in canopy air, ε_c is the emissivity of leaf surface, σ [= 5.67×10-8 W m^{-2} K^{-4}] is Stephan-Boltzmann constant, T_c and T_a [K] are temperature of leaf and canopy air, respectively, w_l [kg m^{-3}] is the fog water content, and a constant $k_l = 1.44\times10^{-4}$ [m^2 kg^{-1}]. The visible and near-infrared bands of both the direct and diffuse radiation fluxes are also calculated independently by using different scattering coefficients depending on leaf properties by the geometrical scheme[35),36)]. Similarly to the sun-shade model[19)], leaves in each canopy layer are separated into two fractions, sun-lit and shaded leaves, and the stomatal resistance for each fraction of leaves is calculated independently. Moreover, the energy budget by (2-6) is also calculated for sun-lit and shaded leaves of each canopy layer separately.

Above sub-models are closely related to each other and iterative calculations are needed to numerically solve some equations strictly. In the model calculation, a small time step (typically 5 sec) is used to reduce the iteration among sub-models in a single time step.

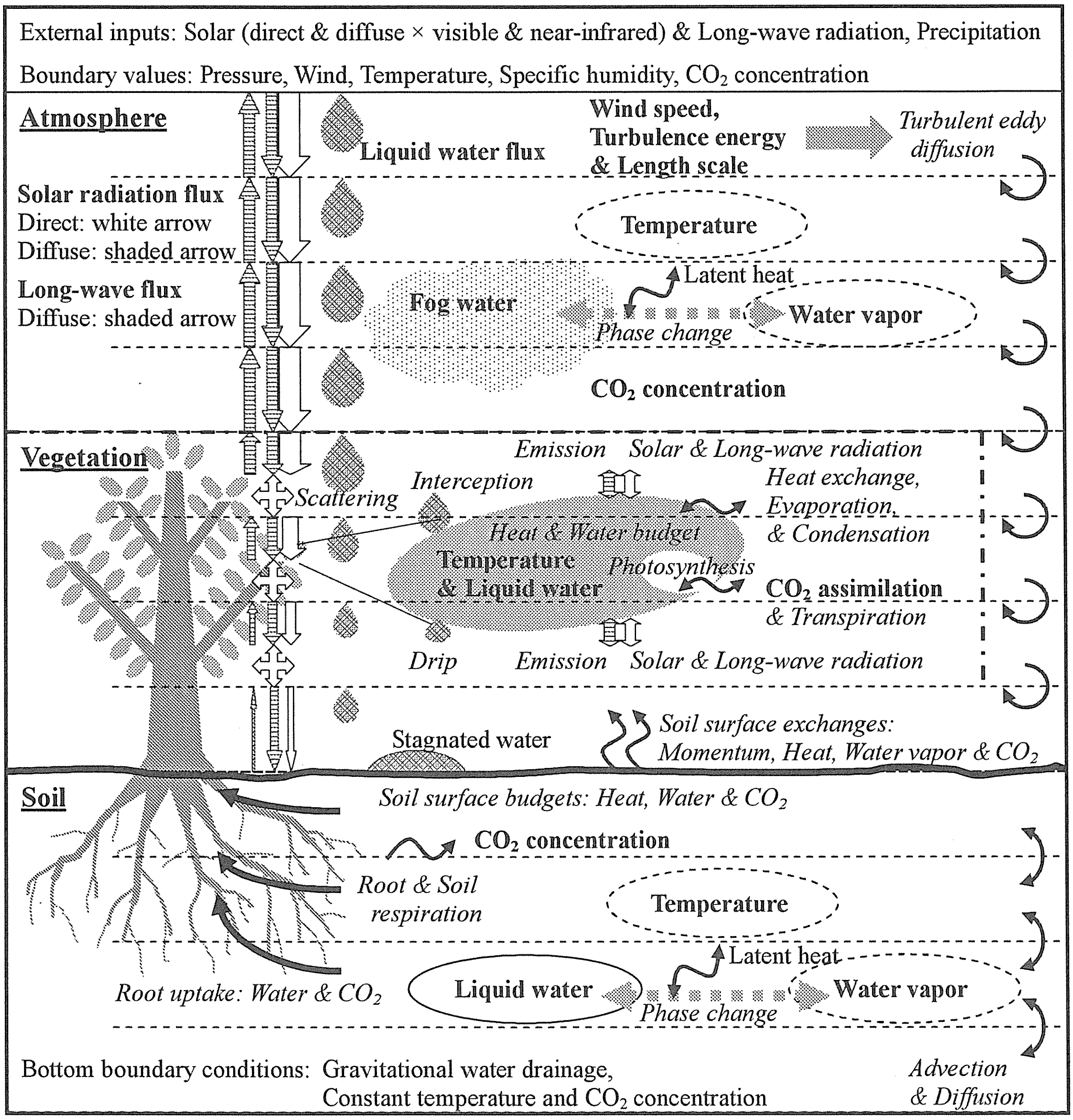

Fig. 2-1 Schematic illustration of modeled processes in the atmosphere-soil-vegetation system. Words in Bold letters are main variables of the model basic equations (2-1) to (2-14) and calculated at each layer in the atmosphere, soil, or vegetation. Words in Italic letters are processes to determine the variables considered in the model.

3. Atmosphere Sub-model

Details of the atmosphere sub-model are presented in this chapter. Equations for atmospheric variables are described at first. Then, the bottom boundary conditions at the soil surface are expressed.

3.1 Atmospheric Variables

The atmosphere sub-model calculates atmospheric variables by numerically solving one-dimensional diffusion equations for the horizontal wind speed components u and v [m s^{-1}], potential temperature θ [K], specific humidity q_a [kg kg^{-1}], fog water content w_f [kg kg^{-1}], turbulence kinetic energy e [m^2 s^{-2}], turbulence length scale λ [m], and CO_2 concentration c_{co2} [ppmv]. By using φ for these variables, one-dimensional diffusion equations are described in the same form as

$$\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial z} K_z \frac{\partial \phi}{\partial z} + F_\phi, \qquad (3\text{-}1)$$

where K_z [m^2 s^{-1}] is the vertical turbulence diffusivity calculated by the turbulence closure model by Yamada[28]. The last term F_φ is a forcing term, and exchanges between the vegetation and canopy air are considered in this term as the volume source/sink of momentum, heat, water in liquid and gas phases, turbulence energy, and CO_2.

The forcing terms for u, v, θ, q_a, e, $e\lambda$, w_f, and c_{co2} are expressed, respectively as

$$F_u = f(v - v_g) - ac_D|\mathbf{u}|u, \qquad (3\text{-}2)$$

$$F_v = -f(u - u_g) - ac_D|\mathbf{u}|v, \qquad (3\text{-}3)$$

$$F_\theta = (H_r + aH_c - lE_f - lE_{pr})/(\rho C_p), \qquad (3\text{-}4)$$

$$F_q = [\ a(E_d + E_s) + E_f + E_{pr}\ ]/\rho, \qquad (3\text{-}5)$$

$$F_e = P_{es} + P_{eb} - D_{ev} + P_{ec}, \qquad (3\text{-}6)$$

$$F_\lambda = P_{\lambda s} + P_{\lambda b} - D_{\lambda v} + P_{\lambda c}, \qquad (3\text{-}7)$$

$$F_w = -(E_f + E_{col} + aE_{cap})/\rho, \qquad (3\text{-}8)$$

and

$$F_{co2} = -M_a a A_n/\rho, \qquad (3\text{-}9)$$

where f [s^{-1}] is the Coriolis parameter, u_g [m s^{-1}] and v_g [m s^{-1}] are geostrophic wind components, c_D is the drag coefficient of leaf, $|\mathbf{u}|$ [m s^{-1}] is wind speed, a [m^2 m^{-3}] is leaf area density, l [J kg^{-1}] is the latent heat of vaporization, ρ [kg m^{-3}] is the air density, C_p [J kg^{-1} K^{-1}]

is the specific heat of air, M_a [kg mol^{-1}] is the molecular weight of air, and A_n [μmol m^{-2} s^{-1}] is the net CO_2 assimilation rate. Terms on the right-hand side of (3-6) and (3-7) are shear production, buoyancy production, dissipation by viscosity, and production by leaf surface, expressed as[11)]

$$P_{es} = 2K_M\left\{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right\}, \tag{3-10}$$

$$P_{eb} = 2K_H \frac{g}{\theta}\frac{\partial \theta}{\partial z}, \tag{3-11}$$

$$D_{ev} = 2e^{3/2}/(B_1\lambda), \tag{3-12}$$

$$P_{ec} = 2ac_D|\mathbf{u}|^{3/2}, \tag{3-13}$$

$$P_{\lambda s} = \lambda E_1 P_{es}/2, \tag{3-14}$$

$$P_{\lambda b} = \lambda E_1 P_{eb}/2, \tag{3-15}$$

$$D_{\lambda v} = \frac{1}{2}\left\{1 + E_2\left(\frac{\eta\lambda}{kz}\right)^2\right\}, \tag{3-16}$$

and
$$P_{\lambda c} = \lambda P_{ec}/2, \tag{3-17}$$

where g [m s^{-2}] is the gravity acceleration, $(B_1, E_1, E_2) = (10.1, 1.8, 1.33)$ constants of the turbulent closure model, k [= 0.4] the von Kármán's constant. The terms on the right-hand side of (3-8) are the production or dissipation of fog water by phase change, accretion with rain droplets, and capture by leaf surface, respectively. The net CO_2 assimilation rate A_n in (3-9) is determined by the vegetation sub-model as described in the following chapter.

When fog water exists in unsaturated air, it evaporates. On the other hand, fog water is generated and increases in saturated air. It is assumed that the evaporation and condensation of fog water take place within an infinitesimally short period δt according to equations

$$E_f\delta t = \rho \min[\ q_{sat}(T_{as}) - q_a, w_f\ ], \tag{3-18}$$

and
$$lE_f\delta t = \rho C_p(T_{as} - T_a), \tag{3-19}$$

where $q_{sat}(T)$ [kg kg^{-1}] represents saturated specific humidity for temperature T [K], and T_{as} [K] is the temperature after the phase change.

3.2 Soil-surface Exchanges

The top boundary conditions for the atmospheric variables are given as input data, and the soil surface boundary conditions are the momentum, heat, water vapor, and CO_2 fluxes calculated by using the soil surface temperature, specific humidity, and CO_2 concentration determined by the soil sub-model. The momentum exchange (τ_x, τ_y) [kg m^{-1} s^{-2}], sensible heat exchange H_0 [W m^{-2}], water vapor exchange E_0 [kg m^{-2} s^{-1}], and CO_2 exchange FC_0 [ppmv m s^{-1}] is calculated by

$$(\tau_x, \tau_y) = \rho c_{M0} |\mathbf{u}_r| (u_r, v_r), \tag{3-20}$$

$$H_0 = C_p \rho c_{H0} |\mathbf{u}_r| (T_{s0} - T_r), \tag{3-21}$$

$$E_0 = \rho c_{E0} |\mathbf{u}_r| (q_{s0} - q_r), \tag{3-22}$$

and

$$FC_0 = c_{H0} |\mathbf{u}_r| (c_{sg0} - c_{co2,r}), \tag{3-23}$$

where $|\mathbf{u}_r|$, u_r, v_r [m s^{-1}], T_r [K], q_r [kg kg^{-1}], and $c_{co2,r}$ [ppmv] are wind speed, wind components, temperature, specific humidity, and CO_2 concentration at a reference height, c_{sg0} [ppmv] is the CO_2 concentration at the soil surface. The exchange coefficients c_{M0}, c_{H0}, and c_{E0} in these equations are calculated by using Monin-Obukhov similarity theory. The equations for these coefficients are expressed as

$$c_{M0} = \frac{k^2}{\{\ln(z_r / z_0) + \psi_M(\zeta_r)\}^2}, \tag{3-24}$$

$$c_{H0} = \frac{k}{\ln(z_r / z_0) + \psi_M(\zeta_r)} \cdot \frac{k}{\ln(z_r / z_T) + \psi_H(\zeta_r)}, \tag{3-25}$$

and

$$c_{E0} = \frac{k}{\ln(z_r / z_0) + \psi_M(\zeta_r)} \cdot \frac{k}{\ln(z_r / z_q) + \psi_E(\zeta_r)}, \tag{3-26}$$

where z_0, z_T, and z_q [m] are roughness lengths for momentum, potential temperature, and specific humidity, respectively, and Ψ_M, Ψ_H, and Ψ_E are defined by using the shear functions Φ_M, Φ_H, Φ_E for surface layer as

$$\psi_M(\zeta_r) = \int_{\zeta_0}^{\zeta_r} \frac{\phi_M(\zeta) - 1}{\zeta} d\zeta, \tag{3-27}$$

$$\psi_H(\zeta_r) = \int_{\zeta_T}^{\zeta_r} \frac{\phi_H(\zeta) - 1}{\zeta} d\zeta, \tag{3-28}$$

and

$$\psi_E(\zeta_r) = \int_{\zeta_q}^{\zeta_r} \frac{\phi_E(\zeta) - 1}{\zeta} d\zeta, \tag{3-29}$$

where ζ is non-dimensional atmospheric stability, defined by using the Monin-Obkhov stability length scale L [m] as

$$\zeta = \frac{z}{L}, \tag{3-30}$$

$$\zeta_0 = \frac{z_0}{L}, \tag{3-31}$$

$$\zeta_T = \frac{z_T}{L}, \tag{3-32}$$

and $$\zeta_q = \frac{z_q}{L}. \tag{3-33}$$

The Monin-Obkhov stability length scale L is expressed as

$$L = -\frac{\left(\dfrac{\tau}{\rho}\right)^{3/2}}{k\dfrac{g}{T_a}\dfrac{H_0}{C_p\rho}}. \tag{3-34}$$

The shear functions used in this model are expressed as[37)]

$$\phi_M = \begin{cases} (1-16.4\zeta)^{-1/4} & -10 < \zeta < 0 \\ 1+\dfrac{8\zeta}{1+\zeta} & \zeta \ge 0 \end{cases}, \tag{3-35}$$

and $$\phi_E = \phi_H = \begin{cases} (1-16.4\zeta)^{-1/2} & -10 < \zeta < 0 \\ 1+\dfrac{8\zeta}{1+\zeta} & \zeta \ge 0 \end{cases}. \tag{3-36}$$

4. Soil Sub-model

In the soil sub-model, the soil temperature, water content, specific humidity in soil pore, and CO_2 concentration are calculated by considering processes of heat conduction, water transport in liquid and gas phases, and CO_2 transport. The water in solid phase is not considered in this model. It may be included in the next version of the model.

4.1 Heat Conduction

The soil sub-model calculates the soil temperature T_s [K] by the heat conduction equation, expressed as

$$\frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z} K_T \frac{\partial T_s}{\partial z} - \frac{lE_b}{C_s \rho_s} - \frac{C_w E_w}{C_s \rho_s} \frac{\partial T_s}{\partial z}, \tag{4-1}$$

where K_T [m^2 s^{-1}], l [J kg^{-1}], and ρ_s [kg m^{-3}] are the thermal conductivity of soil, latent heat of vaporization, and the densities of bulk soil, respectively, C_s and C_w [J m^{-3} K^{-1}] are the volumetric heat capacities of bulk soil and water, respectively. The evaporation rate of soil water E_b [kg m^{-3} s^{-1}] and soil water flux E_w [kg m^{-2} s^{-1}] are defined in the following sections.

The boundary condition for (4-1) at the soil surface is a heat budget equation expressed as

$$(1 - A_b) S_0^{\downarrow} + \varepsilon_b (L_0^{\downarrow} - \sigma T_{s0}{}^4) = H_0 + G_0 + H_{p0}, \tag{4-2}$$

where A_b and ε_b are the reflectivity and emissivity of soil surface, respectively, σ [= 5.67×10^{-8} W m^{-2} K^{-4}] is Stephan-Boltzmann constant, $S_0^{\downarrow}$ [W m^{-2}] and $L_0^{\downarrow}$ [W m^{-2}] are downward solar and long-wave radiation fluxes at the surface, respectively, T_{s0} [K] is the soil surface temperature. This equation has no latent heat term, which is usually included on the right-hand side of the ground surface heat budget equation for bare soil. This is because the model is designed to deal with the water vapor transport in soil explicitly and to calculate the latent heat exchange caused by evaporation of soil water at each layer of soil as volume source or sink term expressed by the second term on the right-hand side of (4-1). The terms on the right-hand side of (4-2) are expressed as

$$H_0 = C_p \rho c_{H0} |\mathbf{u}_r| (T_{s0} - T_r), \tag{4-3}$$

$$G_0 = C_s \rho_s K_T \left. \frac{\partial T_s}{\partial z} \right|_{z=0}, \tag{4-4}$$

and

$$H_{p0} = C_w P_{r0} (T_{s0} - T_p), \tag{4-5}$$

where C_p [J kg^{-1} K^{-1}], ρ [kg m^{-3}], and c_{H0} are the specific heat of air, air density, and heat exchange coefficient between leaf and canopy air, respectively, $|\mathbf{u}_r|$ [m s^{-1}] and T_r [K] are wind speed and temperature at a reference height of the atmosphere, respectively, and P_{r0} [kg m^{-2} s^{-1}] and T_p [K] are precipitation intensity and temperature determined in the vegetation sub-model, respectively. The cooling or warming of soil caused by precipitation (H_{p0}) is assumed to occur at soil surface. In general, the amplitude of diurnal variation in soil temperature decreases exponentially with depth and is almost negligible at 50 cm. Thus, a constant soil temperature is used for the bottom boundary condition for (4-1).

4.2 Liquid Water Transport

The soil sub-model calculates the volumetric soil water content η_w [m^3 m^{-3}] Richards equation[29), expressed as

$$\frac{\partial \eta_w}{\partial t} = -\frac{1}{\rho_w}\left(\frac{\partial E_w}{\partial z} + E_t + E_b\right), \tag{4-6}$$

where ρ_w [kg m^{-3}] is the densities of water. Terms on the right hand side of (4-6) are the soil water flux E_w [kg m^{-2} s^{-1}], root uptake rate E_t [kg m^{-3} s^{-1}], and evaporation rate of soil wate E_b [kg m^{-3} s^{-1}], respectively, and calculated by

$$E_w = -\rho_w\left(D\frac{\partial \eta_w}{\partial z} + K\right), \tag{4-7}$$

$$E_t(z) = \int_0^{H_T} R_w(z;z')a(z')E_s(z')dz', \tag{4-8}$$

and $$r_b E_b = \rho\left[q_{sat}(T_s) - q_s\right], \tag{4-9}$$

where K [m s^{-1}] is the hydraulic conductivity of soil, $E_s(z')$ [kg m^{-2} s^{-1}] is the transpiration rate of unit leaf area at a height of z', and H_T [m] is the height of the canopy layer. Parameter $R_w(z;z')$ [m^{-1}] represents spatial redistribution of water taken by root at a depth of z to transpiration by leaves at the height of z'. The soil water diffusivity D [m^2 s^{-1}] is expressed as

$$D = K\frac{\partial \Psi}{\partial \eta_w}, \tag{4-10}$$

where Ψ [m] is the soil water potential. For Ψ and K, the model uses the empirical equations[38)], express as

$$\Psi = \Psi_s\left(\frac{\eta_w}{\eta_{ws}}\right)^{-b}, \tag{4-11}$$

$$K = K_s\left(\frac{\eta_w}{\eta_{ws}}\right)^{2b+3}, \tag{4-12}$$

where Ψ_s [m], K_s [m s^{-1}], η_{ws} [m^3 m^{-3}], and b are the saturated soil water potential, saturated hydraulic conductivity, saturated volumetric soil water content, and empirical constant, respectively. For the evaporation resistance r_b [s m^{-1}], the model uses the empirical equation[39)], expressed as

$$r_b = 0.02F_1(\eta_{ws} - \eta_w)^{F_2} D_w^{-1}, \tag{4-13}$$

where D_w [m^2 s^{-1}] is the molecular diffusivity for water vapor in air, F_1 and F_2 are the empirical constants depending on the soil type. When soil is dry, soil water exists only in soil micro-pores and evaporation is restrained. This effect is included in the equation for r_b. In contrast to this, the condensation of water vapor in soil pores occurs not only at micro-pores but also at any surface of soil particles. This means that the formulation for the evaporation of soil water cannot be applied to the condensation of soil water. Thus, the model uses the assumption that the condensation of water vapor in soil pores takes place within an infinitesimal period δt according to the equations

$$E_b \delta t = \rho(\eta_{ws} - \eta_w)[q_{sat}(T_{ss}) - q_s], \tag{4-14}$$

and

$$lE_b \delta t = -C_s \rho_s (T_{ss} - T_s), \tag{4-15}$$

where q_s [kg kg^{-1}] is the specific humidity of air in soil pore space, T_{ss} [K] is the soil temperature after the condensation of water vapor in soil pores.

If the precipitation is strong enough to saturate the surface soil, the water in excess stagnates at soil surface. This stagnated water R_s [kg m^{-2}] is calculated by

$$\frac{dR_s}{dt} = P_{r0} + E_{w0}, \tag{4-16}$$

where soil water flux at the surface E_{w0} [kg m^{-2} s^{-1}] becomes the precipitation intensity at the surface $-P_{r0}$ [kg m^{-2} s^{-1}] when the surface soil is not saturated, and has a value $E_{w0} = -\rho_w K_s|_{z=0}$ when the surface soil is saturated. The soil surface water is used for calculation of heat capacity of the soil surface.

4.3 Water Vapor Transport

The soil sub-model calculates the specific humidity of air in soil pore space q_s [kg kg^{-1}] by diffusion equation, expressed as

$$\frac{\partial[(\eta_{ws} - \eta_w)q_s]}{\partial t} = \frac{\partial}{\partial z} D_w f_a(\eta_w) \frac{\partial q_s}{\partial z} + \frac{E_b}{\rho}, \tag{4-17}$$

where $f(\eta_w)$ is the coefficient for distortion of pore (tortuosity), and expressed by as[40]

$$f(\eta_w) = (\eta_{ws} - \eta_w)/1.5. \tag{4-18}$$

Considering the continuity with the water vapor flux in the atmosphere at the soil surface, the boundary condition for (4-17) is expressed as

$$-\rho D_w f(\eta_{w0}) \left.\frac{\partial q_s}{\partial z}\right|_{z=0} = E_0 - E_{b0}, \tag{4-19}$$

where E_{b0} [kg m^{-2} s^{-1}] is the direct evaporation from the thin surface layer to the atmosphere, obtained by integrating E_b in the layer (0 to δz_0). Variable E_0 [kg m^{-2} s^{-1}] is water vapor flux from soil surface to the atmosphere expressed by

$$E_0 = \rho c_{E0} |\mathbf{u}_r| (q_{s0} - q_r), \qquad (4\text{-}20)$$

where q_r [kg kg^{-1}] is specific humidity at a reference height of the atmosphere. Concerning the bottom boundary condition for (4-17), no water vapor flux is assumed.

4.4 CO_2 Transport

In the soil sub-model, the soil CO_2 model[30), 31)] is incorporated to calculate the CO_2 concentration in the soil layers. In this model, the convective and diffusive transports of CO_2 in both aqueous and gas phases are considered in the mass conservation of CO_2 in unsaturated soil. It also assumes the equilibrium between the aqueous phase CO_2 concentration c_{sa} [ppmv] and gas phase CO_2 concentration c_{sg} [ppmv], expressed as

$$c_{sa} = K_H R T_s c_{sg}, \qquad (4\text{-}21)$$

where K_H [mol m^{-3} Pa^{-1}] and R [8.314 J mol^{-1} K^{-1}] are Henry's law constant and gas constant, respectively. The constant K_H for CO_2 is calculated by[41)]

$$K_H = \frac{3.4 \times 10^{-2}}{101.325} \exp\left[-2400 \left(\frac{1}{T_s} - \frac{1}{T_{25}} \right) \right], \qquad (4\text{-}22)$$

where T_{25} [K] is the absolute temperatures at 25 °C. By using this relationship, conservation equations of CO_2 mass in the soil, which is the sum of the gas and aqueous phases ($(\eta_{ws} - \eta_w) c_{sg} + \eta_w c_{sa}$), are expressed only by the function of c_{sg} as,

$$\frac{\partial}{\partial t} V_E c_{sg} = \frac{\partial}{\partial z} D_E \frac{\partial c_{sg}}{\partial z} - \frac{\partial}{\partial z} E_E^* c_{sg} - E_t^* K_H R T_s c_{sg} + S_{CO2}, \qquad (4\text{-}23)$$

where $V_E = (\eta_{ws} - \eta_w) + K_H R T_s \eta_w, \qquad (4\text{-}24)$

$$D_E = (\eta_{ws} - \eta_w) D_{cg} + K_H R T_s \eta_w D_{ca}, \qquad (4\text{-}25)$$

$$E_E^* = E_a^* + K_H R T_s E_w^*, \qquad (4\text{-}26)$$

and $E_a^* = E_{w,BOT}^* - E_w^* - \int_{BOT}^{z} (E_t^* + E_b^*) \delta z, \qquad (4\text{-}27)$

Terms on the right-hand side of (4-23) are the diffusion, advection, root uptake, and production, respectively. The first and second terms on the right hand side of (4-24) to (4-26) represent values for gas and aqueous phases, respectively. Variables E_w^* [m^3 m^{-2} s^{-1}], E_t^*, and E_b^* [m^3 m^{-3} s^{-1}] are the volumetric value of the liquid water flux E_w, root uptake E_t, and evaporation rate E_b of soil water in (4-6), respectively. To determine the volumetric air flux in soil E_a^* [m^3 m^{-2} s^{-1}], it is assumed that the soil air flux is zero at the bottom soil boundary and occurs to compensate the air volume change in a soil layer due to the soil water flux, evaporation, and root uptake, expressed as (4-27). The CO_2 concentration in the root-uptake water is assumed to be the same as that in the soil water. The root-uptake CO_2 is included in the calculation of A_n, although its effect is very small.

Parameters D_{cg} and D_{ca} [m^2 s^{-1}] are the diffusivities of soil CO_2 in gas and aqueous phases, respectively, expressed as

$$D_{cg} = f_{cg}(\eta_w) D_{cg0} \frac{p_0}{p_s}\left(\frac{T_s}{T_0}\right)^n , \tag{4-28}$$

and $$D_{ca} = f_{ca}(\eta_w) D_{ca0} + A_{dis} E_w^* , \tag{4-29}$$

where $f_{cg}(\eta_w)$ and $f_{ca}(\eta_w)$ represent the tortuosity functions for CO_2 diffusion in gas and aqueous phases, respectively, D_{cg0} and D_{ca0} [m^2 s^{-1}] are the molecular diffusivities of CO_2 in gas and aqueous phases, respectively, p_0 and p_s [Pa] are the standard and soil air pressures, respectively, T_0 [K] is the absolute temperatures at 0 °C, and A_{dis} [m] is the dispersion coefficient of soil water flow.

For the CO_2 production term S_{CO2} [ppmv s^{-1}], the soil respiration rate S_{soil} [ppmv s^{-1}] and root respiration rate S_{root} [ppmv s^{-1}] are considered as

$$S_{CO2} = S_{soil} + S_{root} , \tag{4-30}$$

$$S_{soil} = S_{soil0} f_{sz} f_{sm} f_{sT} f_{sC} f_{st} , \tag{4-31}$$

and $$S_{root} = S_{root0} f_{rz} f_{rm} f_{rT} f_{rC} f_{rt} , \tag{4-32}$$

where S_{soil0} and S_{root0} [ppmv m s^{-1}] are the whole soil and root respiration rate at a reference condition, and the functions on the right hand side of (4-31) and (4-32) represent the dependence of the soil and root respiration rates on the depth, moisture, temperature, CO_2 concentration, and time, respectively. In this study, time dependency of soil respiration is not considered, i.e., f_{st} = 1. It is assumed that the root respiration rate is proportional to the leaf area index LAI. In this assumption, f_{rt} = LAI and S_{root0} has a value for LAI = 1. The same formulations[31)] are used for other functions expressed as

$$f_{sz} = a_z \exp(a_z z) , \tag{4-33}$$

$$f_{rz} = \frac{r_i}{\delta z_i} , \tag{4-34}$$

$$f_{sm} = \begin{cases} \dfrac{\log|h| - \log|h_1|}{\log|h_2| - \log|h_1|} & , for\ h_1 \geq h \geq h_2 \\ \dfrac{\log|h| - \log|h_3|}{\log|h_2| - \log|h_3|} & , for\ h_2 > h \geq h_3 \\ 0 & , for\ h > h_1,\ h < h_3 \end{cases} , \quad (4\text{-}35)$$

$$f_{rm} = \frac{1}{1 + (h/h_{50})^b}, \quad (4\text{-}36)$$

$$f_{sT} = f_{rT} = \exp\left[\frac{E}{R}\left(\frac{1}{T_{20}} - \frac{1}{T_s}\right)\right], \quad (4\text{-}37)$$

$$f_{sC} = f_{rC} = \frac{0.21 - c_{sg}}{0.42 - c_{sg} - K_m^*}, \quad (4\text{-}38)$$

where a_z [m^{-1}] is the constant to determine the vertical distribution of soil respiration, r_i and δz_i are the relative root abundance and thickness of the i-th soil layer, h [m] is the pressure head of soil water, K_m^* [$m^3\ m^{-3}$] is Michaelis constant for soil CO_2, T_{20} [K] is the absolute temperatures at 20 °C, h_2=-1.0, h_3=-1.0×10^5, h_{50}=-47.0, b=3, E=50.0×10^3 [J mol^{-1}], K_m^*=0.19 [$m^3\ m^{-3}$][31]. The value h_1 is calculated from the soil water content of $0.99\eta_{ws}$. Variations of the functions f_{sT}, f_{sm}, and f_{sC} are shown in Fig. 4-1. On usual conditions, the soil CO_2 production depends mostly on the soil temperature and water content. The soil surface boundary condition for (4-23) is the CO_2 flux to the atmosphere, which is calculated by the atmosphere sub-model at the previous time step.

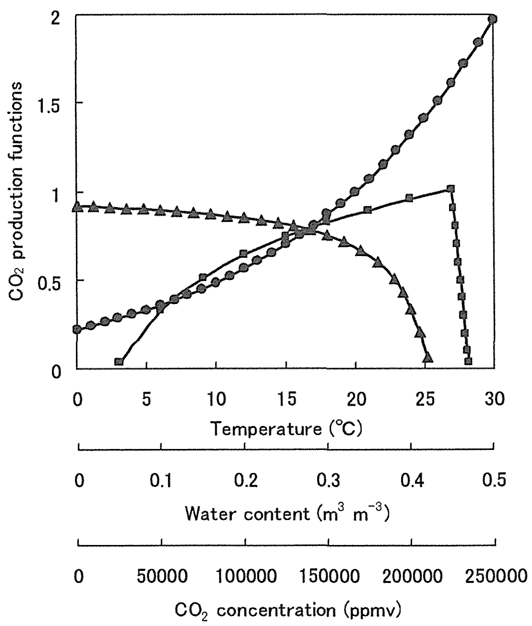

Fig. 4-1 Variations of soil CO_2 production functions for the soil temperature f_{sT} (solid line with closed circles), water content f_{sm} (solid line with closed rectangles), and CO_2 concentration f_{sC} (solid line with closed triangles) for the soil type of this application. The function f_{sm} increase as the soil becomes wet and has its maximum value 1.0 for water content 0.452 $m^3\ m^{-3}$ and decrease to 0 at 99 % of the saturated water content (0.476 $m^3\ m^{-3}$).

4.5 Soil parameters

Soil parameters used in the model for heat and water calculations are the saturated volumetric soil water content η_{ws} [m^3 m^{-3}], saturated water potential Ψ_s [m], saturated hydraulic conductivity K_s [m s^{-1}], exponent in the Clapp and Hornberger equations b, wilting volumetric soil water content η_{wilt} [m^3 m^{-3}], and dry soil heat capacity $C_{s,dry}$ [J m^{-3}]. These values were determined according to the U.S. Department of Agriculture (USDA) texture classes, by using experimental data[38), 42), 43), 44)]. Parameter values are summarized as a lookup table (Table 4-1) for soil type to use in the model calculation.

For CO_2 calculation, the molecular diffusivities of CO_2 in soil air and water D_{cg0} and D_{ca0} [m^2 s^{-1}], dispersion coefficient of soil water flow A_{dis} [m], optimal soil and root respiration rates S_{soil0} and S_{root0} [ppmv m s^{-1}], and constant to determine the vertical distribution of soil respiration a_z [m^{-1}] need to be determined. Parameter a_z (typical value 10.5) has a large influence to the soil CO_2 production, and should be given value for each application. Sensitivity tests were carried out for other parameters, and the results are summarized in Table 4-2.

Table 4-1 List of soil parameters.

Soil type	η_{ws} (m^3 m^{-3})	Ψ_s (m)	K_s (m s^{-1})	b	η_{capa} (m^3 m^{-3})	η_{wilt} (m^3 m^{-3})	$C_{s,dry}$ (J m^{-3})
1. Sand	0.339	-0.069	0.107×10^{-3}	2.790	0.236	0.010	1.47×10^{6}
2. Loamy sand	0.421	-0.036	0.141×10^{-4}	4.260	0.283	0.028	1.41×10^{6}
3. Sandy loam	0.434	-0.141	0.523×10^{-5}	4.740	0.312	0.047	1.34×10^{6}
4. Silt loam	0.476	-0.759	0.281×10^{-5}	5.330	0.360	0.084	1.27×10^{6}
5. Silt	0.476	-0.759	0.281×10^{-5}	5.330	0.360	0.084	1.27×10^{6}
6. Loam	0.439	-0.355	0.338×10^{-5}	5.250	0.329	0.066	1.21×10^{6}
7. Sandy clay loam	0.404	-0.135	0.445×10^{-5}	6.660	0.314	0.067	1.18×10^{6}
8. Silty clay loam	0.464	-0.617	0.204×10^{-5}	8.720	0.387	0.120	1.32×10^{6}
9. Clay loam	0.465	-0.263	0.245×10^{-5}	8.170	0.382	0.103	1.23×10^{6}
10. Sandy clay	0.406	-0.098	0.722×10^{-5}	10.730	0.338	0.100	1.18×10^{6}
11. Silty clay	0.468	-0.324	0.134×10^{-5}	10.390	0.404	0.126	1.15×10^{6}
12. Clay	0.468	-0.468	0.974×10^{-6}	11.550	0.412	0.138	1.09×10^{6}
13. Organic	0.439	-0.355	0.338×10^{-5}	5.250	0.329	0.066	0.84×10^{6}
14. Water	1.000	-0.000	0.000×10^{0}	0.000	1.000	0.000	4.20×10^{6}
15. Bedrock	0.250	-7.590	0.974×10^{-7}	11.550	0.233	0.094	1.50×10^{6}
16. Other	0.421	-0.036	0.134×10^{-5}	11.550	0.283	0.028	1.40×10^{6}

Table 4-2 Parameters and results of sensitivity test for soil CO_2 calculation.

Item	Control case value (Tested values)	Influence for CO_2 calculation
CO_2 diffusivity in soil air (D_{cg0})	1.35×10^{-5} m^2 s^{-1} (0.675×10^{-5}, 2.7×10^{-5} m^2 s^{-1})	Large change in profile, but small change for surface flux.
CO_2 diffusivity in soil water (D_{ca0})	2.0×10^{-9} m^2 s^{-1} (1.0×10^{-9}, 4.0×10^{-9} m^2 s^{-1})	Negligible.
Dispersion coefficient of soil water flow (A_{dis})	0.05 m (0, 0.025, 0.1 m)	Negligible.
Optimal soil respiration rate (S_{soil0})	0.06 ppmv s^{-1} (0.03, 0.12 ppmv s^{-1})	Linearly affect for both profile and flux.
Optimal root respiration rate (S_{root0})	0.01 ppmv s^{-1} (0.005, 0.02 ppmv s^{-1})	Linearly affect for both profile and flux.

5. Vegetation Sub-model

The vegetation sub-model calculates the leaf temperature, leaf surface water, vertical water flux, and CO_2 assimilation by photosynthesis. The CO_2 exchange processes have influence to heat and water exchange processes only in the vegetation sub-model by controlling the transpiration through photosynthesis, and have no direct effect in other sub-models.

5.1 Heat Budget

The leaf temperature T_c [K] is calculated for sun-lit and sun-shaded leaves separately by solving a leaf surface heat budget equation,

$$R_c = H_c + l(E_d + E_s) + H_p, \tag{5-1}$$

where R_c, H_c [J m^{-2} s^{-1}], E_d, E_s [kg m^{-2} s^{-1}], and H_p [J m^{-2} s^{-1}] are the net radiation, sensible heat flux, evaporation rate of leaf surface water, transpiration rate, and cooling by precipitation, respectively, and each term is determined by the leaf temperature of sun-lit and shaded leaves and variables by the atmosphere sub-model and the radiation scheme. The net radiation term is calculated by

$$R_c = \frac{F_{rd}}{f_{lit}}(1 - A_s)S_d^{\downarrow} + F_{rs}\left[(1 - A_s)\left(S_s^{\uparrow} + S_s^{\downarrow}\right) + \varepsilon_c\left(L^{\uparrow} + L^{\downarrow} - 2\sigma T_c^4\right)\right], \tag{5-2}$$

for sun-lit leaves, and

$$R_c = F_{rs}\left[(1 - A_s)\left(S_s^{\uparrow} + S_s^{\downarrow}\right) + \varepsilon_c\left(L^{\uparrow} + L^{\downarrow} - 2\sigma T_c^4\right)\right], \tag{5-3}$$

for sun-shaded leaves, respectively, where F_{rd} and F_{rs} are the shielding coefficients for direct and diffuse radiation fluxes, respectively, f_{lit} is the fraction of sun-lit leaves in each canopy layer, A_s is the scattering coefficient of leaves, which is the sum of leaf reflectivity A_r and transmissivity A_t, S_d and S_s [W m^{-2}] are direct and diffuse solar radiation fluxes, respectively, L is the long-wave radiation flux, ε_c is the emissivity of leaf surface, σ [= 5.67×10-8 W m^{-2} K^{-4}] is Stephan-Boltzmann constant. Other terms are expressed as

$$H_c = \rho C_p c_H |\mathbf{u}|(T_c - T_a), \tag{5-3}$$

$$E_s = \rho\frac{r_d}{R'}\left[q_{sat}(T_c) - q_a\right], \tag{5-4}$$

$$E_d = \rho\frac{r_s}{R'}\left[q_{sat}(T_c) - q_a\right], \tag{5-5}$$

and

$$H_p = C_w F_p P_r\left(T_c - T_p\right), \tag{5-6}$$

where $R' = (r_a r_s + r_a r_d + r_s r_d)$, r_a, r_d, and r_s [s m^{-1}] are resistances of leaf boundary layer, evaporation of leaf surface water and stomata, respectively, ρ [kg m^{-3}] is the air density, C_p

and C_w [J kg^{-1} K^{-1}] are the specific heat of air and water, respectively, c_H is the heat exchange coefficient between leaf and canopy air, $|\mathbf{u}|$ [m s^{-1}] is wind speed, T_a [K] and q_a [kg kg^{-1}] are temperature and specific humidity of canopy air, respectively, $q_{sat}(T_c)$ [kg kg^{-1}] is saturated specific humidity for leaf temperature T_c, F_p is the shielding coefficient for precipitation, and P_r [kg m^{-2} s^{-1}] is the precipitation intensity in the canopy. As the feed back to the atmosphere sub-model, the sensible heat flux H_c and evapotranspiration ($E_d + E_s$) aggregated at each layer are used in (3-4) and (3-5). The aggregation of variables for sun-lit and shaded leaves is took place as

$$\phi = f_{lit}\phi_{lit} + f_{shade}\phi_{shade}, \tag{5-7}$$

where f_{shade} is the fraction of sun-shaded leaves, φ_{lit} and φ_{shade} are variables for sun-lit and shaded leaves, respectively.

The shielding coefficients F_{rd}, F_{rs} F_p account for the inclination of leaf surface and the overlap of leaves, and expressed as

$$F_{rd} = \frac{1-\exp(-k_d a\delta z)}{a\delta z}, \tag{5-8}$$

$$F_{rs} = \frac{1-\exp(-k_s a\delta z)}{a\delta z}, \tag{5-9}$$

$$F_p = \frac{1-\exp(-k_p a\delta z)}{a\delta z}, \tag{5-10}$$

where a [m^2 m^{-3}] is the leaf area density, and k_d, k_s, and k_p are mean projection coefficients of leaves in a layer for direct radiation, diffuse radiation, and precipitation, respectively. Projection coefficients for radiation are determined geometrically from the leaf orientation and the incident radiation angle by the geometrical method[35)] as described in the chapter for radiation scheme. The projection coefficient for precipitation F_p is determined by the same way as that for direct radiation from the zenith.

The leaf boundary layer resistance r_a is assumed to depend only on the aerodynamical characteristic of leaf surface, and expressed as

$$r_a = (c_E|\mathbf{u}|)^{-1}, \tag{5-11}$$

where c_E is the vapor exchange coefficient between leaf and canopy air. The model uses the formulation for the evaporation resistance r_d, expressed as[3)]

$$r_d = \begin{cases} (1-x_d)x_d^{-1}r_a & for \quad q_{sat}(T_c) \ge q_a \\ 0 & for \quad q_{sat}(T_c) < q_a \end{cases}, \tag{5-12}$$

$$x_d = \min\left[1, \left(\frac{w_d}{w_{dw}}\right)^{2/3}\right], \tag{5-13}$$

where w_d and w_{dw} [kg m^{-2}] are the leaf surface water and its value for maximum evaporation. The stomatal resistance r_s is calculated by the Jarvis-type formulation[45], which has been used in many land surface models[4), 6), 7), 8), 9)], and the formulation is expressed as

$$r_s = r_{s,\min} f_r f_s^{-1} f_m^{-1} f_t^{-1}, \tag{5-14}$$

where $r_{s,min}$ [s m^{-1}] is the minimum stomatal resistance, f_r, f_s, f_m, and f_t are stress functions of radiation, soil moisture, canopy humidity, and temperature, respectively. The formulations for f_r, f_m, and f_t [7] and f_s [6] are used. These functions are expressed as

$$f_r = \left(1 + \frac{R_p}{R_{pc}}\right)\left(\frac{R_p}{R_{pc}} + \frac{r_{s,\min}}{r_{s,\max}}\right)^{-1}, \tag{5-15}$$

$$f_s = \min\left(\frac{\eta_w - \eta_{wilt}}{\eta_c - \eta_{wilt}}, 1\right), \tag{5-16}$$

$$f_m = 1 - 0.025\left[e_{sat}(T_a) - e_a\right], \tag{5-17}$$

and $$f_t = 1 - 0.0016(298.0 - T_a)^2. \tag{5-18}$$

where η_w, η_c, and η_{wilt} [m^3 m^{-3}] are volumetric soil water content, field capacity, and wilting soil water content, respectively, e_a and $e_{sat}(T_a)$ [Pa] are the vapor pressure of canopy air and its saturated value for canopy air temperature T_a [K], respectively. The model uses the values[7], $r_{s,max}$ = 5000 (s m^{-1}), R_{pc} = 100 (W m^{-2}) for grass and crops, and R_{pc} = 30 (W m^{-2}) for trees are used. When f_s, f_m, or f_t has values close to 0 or negative, r_s becomes $r_{s,max}$. The stomatal resistance is calculated for sun-lit and shaded leaves at each canopy layer by calculating f_r, f_m, and f_t at the layer and f_s from the average water content in the root zone soil. For the stomatal resistance, another scheme based on the photosynthesis is also included, and it is described later in the section for CO_2 processes.

5.2 Leaf Surface Water

The leaf surface water w_d [kg m^{-2}] is determined by

$$\frac{dw_d}{dt} = E_{\text{int}} - E_d + E_{cap} - P_d, \tag{5-19}$$

where E_{int} and E_{cap} [kg m^{-2} s^{-1}] are the water exchanges due to interception of precipitation by leaves and capture of fog water by leaves, respectively, and P_d [kg m^{-2} s^{-1}] is the drip from leaves. The terms on the right hand side of (5-19) are expressed as

$$E_{\text{int}} = F_p P_r, \tag{5-20}$$

$$E_{cap} = F_f |\mathbf{u}| \rho w_f , \tag{5-21}$$

and
$$P_d = \begin{cases} 0 & for \quad w_d < w_{ds} \\ E_{\mathrm{int}} - E_d + E_{cap} & for \quad w_d = w_{ds} \end{cases} , \tag{5-22}$$

where w_f [kg kg^{-1}] is fog water content, w_{ds} [kg m^{-2}] is maximum leaf surface water, and F_f is the coefficient for interception of fog water, similar to F_p but in horizontal direction. The amount of fog water captured by unit leaf area E_{cap} is proportional to speed of fog water (wind speed $|\mathbf{u}|$), and weight of fog water in unit weight air. When the amount of water on unit area of leaf surface exceeds the threshold value w_{ds}, the excess becomes the drip from leaf surface P_d. The value w_{ds} would naturally depend on shape, surface characteristic, angle, and motion (wind speed) of leaves. However, the model uses a constant value for w_{ds}.

5.3 Vertical Water Flux in Canopy

The vertical liquid water flux in the canopy P_r [kg m^{-2} s^{-1}] is calculated by

$$\frac{dP_r}{dz} = a(E_{\mathrm{int}} - P_d) + E_{pr} - E_{col} , \tag{5-23}$$

where E_{pr} and E_{col} [kg m^{-3} s^{-1}] are the evaporation of rain droplets and capture of fog water by rain droplets, respectively. The input precipitation intensity becomes the boundary value at the canopy top, and a calculated value at the canopy bottom is provided for the surface water budget calculation in the soil sub-model. The terms on the right-hand side of (5-23) are expressed as

$$E_{pr} = \frac{3\rho c_E}{4r\rho_w} P_r \left[q_{sat}(T_p) - q_a \right], \tag{5-24}$$

and
$$E_{col} = \frac{3\rho P_r w_f}{4r\rho_w} , \tag{5-25}$$

where ρ_w [kg m^{-3}] is the densities of water, r [m] is the radius of raindrop. These terms are considered to be proportional to the speed of raindrop relative to the air, and the density of raindrop cross section, and obtained using the assumptions that the specific humidity at the surface of a raindrop has the saturated value for the temperature of the raindrop, that every raindrop has a spherical shape with the same radius r, and that raindrops capture all the fog water in their paths.

5.4 CO_2 Exchange Processes

In the vegetation sub-model, the scheme based on photosynthesis[20), 24)] is incorporated to calculate the CO_2 assimilation rate and stomatal resistance. In this scheme, the CO_2 assimilation rate is calculated by using the Farquhar's formulations[32)] and the relationship between the stomatal resistance and the CO_2 assimilation rate[33), 34)].

The relationship between the stomatal resistance r_s^* [m^2 s μmol^{-1}] (inverse of stomatal conductance g_s [$\mu mol\ m^{-2}\ s^{-1}$]) and the CO_2 net assimilation rate A_n [$\mu mol\ m^{-2}\ s^{-1}$] is expressed as

$$\frac{1}{r_s^*} = g_s = m\frac{A_n}{c_s}\frac{e_s}{e_{sat}(T_c)}p_a + g_{s,\min}, \tag{5-26}$$

where c_s, e_s, $e_{sat}(T_c)$, and p_a [Pa] are the CO_2 partial pressure at leaf surface, vapor pressure at leaf surface, saturated vapor pressure for leaf temperature T_c [K], and atmospheric pressure, respectively. The coefficient m and minimum stomatal conductance $g_{s,min}$ [$\mu mol\ m^{-2}\ s^{-1}$] are empirically determined from observations. The conversion of unit from r_s^* [m^2 s μmol^{-1}] in (5-26) to r_s [s m^{-1}] is necessary to be used in (5-4) and (5-5), expressed as

$$r_s \quad \left[s\ m^{-1}\right] = \left(\frac{p_a}{RT_c}\times 10^6\right) r_s^* \quad \left[m^2\ s\ \mu mol^{-1}\right], \tag{5-27}$$

where R [8.314 J mol^{-1} K^{-1}] is the gas constant. There are many arguments to use this formulation for the stomatal resistance calculation[46), 47), 48), 49)], and many formulations have been proposed[48), 50), 51)]. In this study, the above formulation[33), 34)] is applied to construct the framework of CO_2 calculations at the beginning because it is widely used and its parameters are described well. Other or new formulations will be tested in future works.

The net CO_2 assimilation rate A_n, which is calculated by subtracting the leaf respiration rate R_d [$\mu mol\ m^{-2}\ s^{-1}$] from the assimilation rate, is expressed as

$$A_n = \min(w_c, w_e, w_s) - R_d, \tag{5-28}$$

where the CO_2 assimilation rate is determined as the minimum of three limiting rates, that is the limitation by efficiency of the photosynthetic enzyme system (Rubisco) w_c [$\mu mol\ m^{-2}\ s^{-1}$], limitation by absorbed PAR w_e [$\mu mol\ m^{-2}\ s^{-1}$], and limitation by the capacity of leaf to export the products of photosynthesis w_s [$\mu mol\ m^{-2}\ s^{-1}$], calculated by

$$w_c = V_m\begin{cases}\dfrac{c_i - \Gamma_*}{c_i + K_c(1 + O_2/K_o)} & ,\ for\ C3\ plants \\ 1 & ,\ for\ C4\ plants\end{cases}, \tag{5-29}$$

$$w_e = \alpha f_{PAR} I\begin{cases}\dfrac{c_i - \Gamma_*}{c_i + 2\Gamma_*} & ,\ for\ C3\ plants \\ 1 & ,\ for\ C4\ plants\end{cases}, \tag{5-30}$$

and

$$w_s = V_m\begin{cases}0.5 & ,\ for\ C3\ plants \\ 4000\dfrac{c_i}{p_a} & ,\ for\ C4\ plants\end{cases}, \tag{5-31}$$

where V_m [$\mu mol\ m^{-2}\ s^{-1}$] is the maximum catalytic capacity of Rubisco, c_i [Pa] is the CO_2 partial pressure of leaf interior, Γ_* [Pa] is the CO_2 compensation point, K_c and K_o [Pa] are the

Michaelis-Menten constant for CO_2 and O_2, respectively, O_2 [Pa] is the O_2 partial pressure of leaf interior, α [μmol-CO_2 μmol-photon^{-1}] is the Quantum efficiency (= 0.06 for C3 plants, 0.04 for C4 plants), f_{PAR} is the Constant (= 4.6) to convert PAR unit from [W m^{-2}] to [μmol-photon m^{-2} s^{-1}], I [W m^{-2}] is absorbed PAR by unit leaf area, C3 plants is the dominant species of vegetation (80% of the world's vegetation cover) including all forests and temperate grasses, and C4 plants is principally tropical grasses[24]. Leaf respiration rate is calculated by

$$R_d = f_d V_m, \tag{5-32}$$

where f_d = 0.015 (for C3 plants) or 0.025 (for C4 plants).

Formulations of variables in equations (5-29) to (5-32) are expressed as

$$V_m = V_{m25} a_{vm}^{(T_c - T_{25})/10} f(T_c) \beta_t, \tag{5-33}$$

$$O_2 = 0.209 p_a, \tag{5-34}$$

$$\Gamma_* = 0.21 \frac{K_c}{2K_o} O_2, \tag{5-35}$$

$$K_c = K_{c25} a_{Kc}^{(T_c - T_{25})/10}, \tag{5-36}$$

and
$$K_o = K_{o25} a_{Ko}^{(T_c - T_{25})/10}, \tag{5-37}$$

where V_{m25} [μmol m^{-2} s^{-1}], T_{25} [K], K_{c25}, and K_{o25} [Pa] are the values of V_m, temperature, K_c, and K_o at 25 °C, respectively. The model uses the values[20], $\alpha_{vm} = 2.4$, $K_{c25} = 30$, $K_{o25} = 30000$, $\alpha_{Kc} = 2.1$, $\alpha_{Ko} = 1.2$. Variables in (5-33) are expressed as

$$f(T_c) = \left[1 + \exp\left(\frac{710T_c - 220000}{RT_c} \right) \right]^{-1}, \tag{5-38}$$

$$\beta_t = \sum_i w_i r_i, \tag{5-39}$$

and
$$w_i = \begin{cases} \dfrac{\eta_w^i - \eta_{wilt}^i}{\eta_c^i - \eta_{wilt}^i} \le 1 & , \quad for\ T_s^i > 273.16 \\ 0.01 & , \quad for\ T_s^i \le 273.16 \end{cases}, \tag{5-40}$$

where r_i is relative root abundance in the i-th soil layer, and T_s [K] is the soil temperature.

To calculate A_n, the amount of PAR absorbed by a unit leaf, leaf temperature, soil water content, and CO_2 partial pressure of leaf interior c_i are needed. The absorption of PAR is calculated for the sun-lit and shaded leaves separately by the radiation scheme. As described above, the leaf temperature is also calculated for the sun-lit and shaded leaves. Therefore, the

CO_2 assimilation and stomatal resistance are calculated separately for the sun-lit and shaded leaves. For the calculations of A_n and r_s^*, unknown variables c_i, c_s, and e_s need to be determined. By assuming that A_n and CO_2 fluxes from the canopy air to the leaf surface and the leaf surface to the leaf interior are the same, c_i and c_s are related to the CO_2 partial pressure of canopy air c_a [Pa] as

$$A_n = \frac{c_a - c_i}{(1.37 r_{lb} + 1.65 r_s^*) p_a} = \frac{c_a - c_s}{1.37 r_{lb} p_a} = \frac{c_s - c_i}{1.65 r_s^* p_a}, \qquad (5\text{-}41)$$

where r_{lb} [m^2 s μmol^{-1}] is the leaf boundary layer resistance for CO_2 exchange between leaf and canopy air, which is determined from the wind speed of each canopy layer calculated by the atmosphere sub-model. Also, the vapor pressure at the leaf surface e_s is related to the vapor pressures of the leaf interior e_i (= $e_{sat}(T_c)$) [Pa] and the canopy air e_a [Pa] as

$$\frac{e_a - e_i}{r_{lb} + r_s^*} = \frac{e_a - e_s}{r_{lb}} = \frac{e_s - e_i}{r_s^*}. \qquad (5\text{-}42)$$

In the model calculation, the above equations are solved by iterative way to determine r_s^* and A_n for each integration time step. At first, A_n is calculated by using a initial value of c_i (= 0.7 c_a), and this value and c_a are used to determine c_s by (5-41). Then, r_s^* and e_s are determined by solving simultaneous equations (5-26) and (5-42). With derived values of A_n and r_s^*, c_i is calculated by (5-41). The recalculation of A_n and r_s^* is carried out by using new c_i. This procedure is repeated until the value of c_i converges into a specified threshold. The net CO_2 assimilation rates A_n calculated for sun-lit and shaded leaves are aggregated by (5-7), and used in (3-9) for CO_2 calculation in the atmosphere sub-model.

5.5 Vegetation parameters

Vegetation parameters are categorized into two types. One is leaf surface property, and the other is vegetation structure. The former includes the leaf surface reflectivity A_r, transmissivity A_t, emissivity ε_c, maximum leaf surface water w_{ds} [kg m^{-2}], leaf surface water for maximum evaporation w_{dw} [kg m^{-2}], drag coefficient c_D, heat exchange coefficient c_H, water vapor exchange coefficient c_E, minimum stomatal resistance $r_{s,min}$ [s m^{-1}], zenith angle of leaf orientation θ_l, empirical constant m to relate CO_2 assimilation rate and the stomatal resistance, and maximum catalytic capacity of Rubisco at 25 °C V_{m25} [μmol m^{-2} s^{-1}]. The latter has the distribution of leaf area density a [m^2 m^{-3}] and root distribution, which is expressed as the fraction of root uptake of water in each soil layer to total uptake. The model has no lookup table for the later types of parameters, and they are given the values for actual vegetation conditions. Values from literature were used for most of the leaf surface properties as listed in Table 5-1 and 5-2.

Table 5-1 List of vegetation parameters (I).

Item	Value	Reference
Drag coefficient of leaf (c_D)	0.2	Meyers and Paw U (1986)[12]
Heat exchange coefficient (c_H)	0.06	Kondo and Watanabe (1992)[52]
Vapor exchange coefficient (c_E)	0.06	Kondo and Watanabe (1992)[52]
Maximum leaf water (w_{ds})	0.2 kg m^{-2}	Noilhan and Planton (1989)[6]
Minimum stomatal resistance ($r_{s,min}$)	Crop/grass: 100 s m^{-1}, Others: 200 s m^{-1}	Dickinson et al. (1993)[7]
Leaf emissivity (ε_c)	0.98	Nagai (2002)[16]
Zenith angle of leaf orientation (θ_l)	Uniform type: 60°, Wheat: 70°	Nagai (2003)[17]

Table 5-2 List of vegetation parameters (II). The reflectivity Ar and transmissivity At are based on Dorman and Sellers (1989)[53], the maximum catalytic capacity of Rubisco at 25 °C V_{m25} and empirical constant m are from Bonan (1995)[20] and Sellers et al. (1996)[24].

Vegetation type	A_r		A_t		V_{m25}[20]	m[20]
	Visible	N-I	Visible	N-I		
Grass	0.110	0.580	0.070	0.250	33.0	9.0
Broad deciduous	0.100	0.450	0.050	0.250	33.0	9.0
Needle	0.070	0.350	0.050	0.100	33.0	6.0
Crop	0.110	0.580	0.070	0.250	50.0	9.0
C4-grass	0.110	0.580	0.070	0.250	33.0	5.0
Broad-evergreen	0.100	0.450	0.050	0.250	50.0	9.0
Shrub	0.100	0.450	0.050	0.250	17.0	9.0

6. Radiation Scheme

The radiation scheme calculates the downward and upward fluxes of the solar radiation and long-wave radiation in the canopy, and provides the radiation energy input for heat budget calculations at the soil surface and canopy layers. It was modified to treat the direct and diffuse radiation fluxes separately[17]. The visible and near-infrared bands of both the direct and diffuse radiation fluxes are also calculated independently by using different scattering coefficients depending on leaf properties by the geometrical scheme[35),36)].

6.1 Radiation Transmission

The solar radiation flux is partitioned into four (visible and near-infrared parts in direct and diffuse) components and calculated separately. The transmission equations for the downward direct solar radiation flux $S_d^{\downarrow}$ [W m^{-2}] and the downward and upward diffuse solar radiation fluxes, $S_s^{\downarrow}$ and $S_s^{\uparrow}$ [W m^{-2}], are expressed as

$$\frac{dS_d^{\downarrow}}{dz} = (aF_{rd} + a'_w + A'_w)S_d^{\downarrow}, \quad (6\text{-}1)$$

$$\frac{dS_s^{\downarrow}}{dz} = \left[aF_{rs}\left(1 - f_{sf}\right) + a'_w + A'_w\right]S_s^{\downarrow} - (aF_{rs}f_{sb} + A'_w)S_s^{\uparrow} - aF_{rd}f_{df}S_d^{\downarrow}, \quad (6\text{-}2)$$

and

$$\frac{dS_s^{\uparrow}}{dz} = -\left[aF_{rs}\left(1 - f_{sf}\right) + a'_w + A'_w\right]S_s^{\uparrow} + (aF_{rs}f_{sb} + A'_w)S_s^{\downarrow} + aF_{rd}f_{db}S_d^{\downarrow}, \quad (6\text{-}3)$$

where a [m^2 m^{-3}] is the leaf area density, f_{db}, f_{df}, f_{sb}, and f_{sf} are the backward and forward scattering coefficients for direct and diffuse radiation fluxes, respectively, and a'_w ($= a_w/\delta z$) and A'_w ($= A_w/\delta z$) are the absorptivity and reflectivity of liquid water in canopy air. As described before in the chapter for the vegetation sub-model, the shielding coefficients for direct and diffuse radiation fluxes F_{rd} and F_{rs} are expressed as

$$F_{rd} = \frac{1 - \exp\left(-k_d a\delta z\right)}{a\delta z}, \quad (6\text{-}4)$$

$$F_{rs} = \frac{1 - \exp\left(-k_s a\delta z\right)}{a\delta z}, \quad (6\text{-}5)$$

where k_d and k_s are mean projection coefficients of leaves in a layer for direct radiation and diffuse radiation, respectively. In the scattering coefficients, the reflection and transmission of leaves are considered and the reflectivity and transmissivity of a leaf can be applied. The residual portion of intercepted radiation after subtracting the scattering is used as the absorbed radiation in the heat balance calculation at the leaf surface. Concerning the visible and near-infrared bands, the same equations are used, but different values of the reflectivity and transmissivity of a leaf are applied in the scattering coefficients. These coefficients are described in the following sections.

The long-wave radiation fluxes $L^{\downarrow}$ and $L^{\uparrow}$ [W m^{-2}] are assumed to have only diffuse radiation component, and the formulations are expressed as

$$\frac{dL^{\downarrow}}{dz} = aF_{rs}\left[\left(1-f_{sf}\right)L^{\downarrow} - f_{sb}L^{\uparrow} - \varepsilon_c \sigma T_c^4\right] + k_l w_l \left(L^{\downarrow} - \sigma T_a^4\right), \tag{6-6}$$

and
$$\frac{dL^{\uparrow}}{dz} = -aF_{rs}\left[\left(1-f_{sf}\right)L^{\uparrow} - f_{sb}L^{\downarrow} - \varepsilon_c \sigma T_c^4\right] - k_l w_l \left(L^{\uparrow} - \sigma T_a^4\right), \tag{6-7}$$

where ε_c is the emissivity of leaf surface, σ [= 5.67×10-8 W m^{-2} K^{-4}] is Stephan-Boltzmann constant, T_c and T_a [K] are temperature of leaf and canopy air, respectively, w_l [kg m^{-3}] is the liquid water concentration in the air, and a constant k_l = 1.44×10^{-4} [m^2 kg^{-1}]. Since most of the long-wave radiation flux intercepted by leaves is absorbed, it can be assumed that transmission through the leaf is negligible and the fraction of intercepted radiation not absorbed is the reflection.

The shielding coefficients and scattering coefficients are determined from the solar zenith angle and leaf orientation distribution in geometrical ways[35), 36)]. The concept of leaf shielding coefficients can be easily expanded to the separate treatment of direct and diffuse solar radiation fluxes for the photosynthesis calculation as the sun-shade model[19)]. Leaves in each canopy layer are separated simply into two fractions, sun-lit leaves f_{lit} and sun-shaded leaves f_{shade}. The fraction of sun-lit leaves for each layer is calculated by dividing the intercepted direct solar radiation flux by the mean beam intensity, expressed as,

$$f_{lit} = \frac{aF_{rd}S_d^{\downarrow}}{\left\langle S_d^{\downarrow}\right\rangle}, \tag{6-8}$$

where $\langle S_d^{\downarrow}\rangle$ is the mean beam intensity of the direct solar radiation incident on the sun-lit leaf surface, and expressed as

$$\left\langle S_d^{\downarrow}\right\rangle = k_d S_{d,top}^{\downarrow}, \tag{6-9}$$

where the subscript *top* represents the value at the canopy top. The stomatal resistance for each fraction of leaves is calculated independently in the vegetation sub-model. Moreover, the energy budget of each fraction of leaves is also calculated separately. Therefore, the leaf temperature T_c has two values for sun-lit leaves $T_{c,lit}$ and sun-shaded leaves $T_{c,shade}$. To be used in (6-6) and (6-7), these values are aggregated by

$$T_c^4 = f_{lit}T_{c,lit}^4 + f_{shade}T_{c,shade}^4, \tag{6-10}$$

where f_{lit} and f_{shade} are the fractions of sun-lit and shaded leaves, respectively.

To use this radiation scheme, the downward fluxes of the four solar radiation components at the canopy top are needed as boundary conditions. When the model uses the output from atmospheric models, all the radiation components can be provided. However, they are not always available when the model uses observation data. It is the usual situation for the observation data that only the global solar radiation flux is available as the model input. Therefore, a method to estimate the four radiation components from the observed global solar radiation flux is necessary. The mode uses the empirical method[54)] as follows. The potential solar radiation fluxes in clear sky condition are expressed for four components: direct and diffuse flux in visible bad S_{dV} and S_{sV} [W m^{-2}], and direct and diffuse flux in near-infrared band S_{dN} and S_{sN} [W m^{-2}], respectively, as

$$S_{dV} = 600\exp\left[-0.185\left(\frac{p}{p_0}\right)m\right]\cos\theta_s, \tag{6-11}$$

$$S_{sV} = 0.4\left(600\cos\theta_s - S_{dV}\right), \tag{6-12}$$

$$S_{dN} = (720 - w)\exp\left[-0.06\left(\frac{p}{p_0}\right)m\right]\cos\theta_s, \tag{6-13}$$

and
$$S_{sN} = 0.6\left[(720 - w)\cos\theta_s - S_{dN}\right], \tag{6-14}$$

where
$$w = 1320\times 10^{f}:\ f = -1.1950 + 0.4459\log_{10} m - 0.0345\log_{10}^2 m, \tag{6-15}$$

$m = (\cos\theta_s)^{-1}$, θ_s [radian] is the solar zenith angle, and p and p_0 [hPa] are surface pressure and its reference value (1013.25 hPa), respectively. The input global solar radiation flux S_{in} [W m^{-2}], which is usually smaller than the sum of potential radiation flux components ($S_{dV} + S_{sV} + S_{dN} + S_{sN}$) by the influence of clouds and aerosols, is partitioned into visible and near-infrared band components by using the ratio of potential flux values ($S_{dV} + S_{sV} : S_{dN} + S_{sN}$). Then, direct and diffuse flux components for each band are calculated by using the fractions of direct component for visible and near-infrared band,

$$f_{dV} = \frac{S_{dV}}{S_{dV} + S_{sV}}\left[1 - \left(\frac{0.9 - RATIO}{0.7}\right)^{2/3}\right], \tag{6-16}$$

$$f_{dN} = \frac{S_{dN}}{S_{dN} + S_{sN}}\left[1 - \left(\frac{0.88 - RATIO}{0.68}\right)^{2/3}\right], \tag{6-17}$$

where $RATIO = S_{in}/(S_{dV} + S_{sV} + S_{dN} + S_{sN})$ and $0.2 \le RATIO \le 0.9$ for (6-16) 0.88 for (6-17).

6.2 Reflectivity and Absorptivity of Water in Air

The reflectivity A_w and absorptivity a_w of water in the air are the function of liquid water concentration w_l [kg m^{-3}] in the air, and calculated by[55)]

$$A_w = \begin{cases} \dfrac{(0.01k_r)^{0.55}}{0.01}\dfrac{w_l\delta z}{\cos\theta_s} & for\ \ \dfrac{w_l\delta z}{\cos\theta_s} < 0.01 kg/m^2 \\ \left(\dfrac{k_r w_l \delta z}{\cos\theta_s}\right)^{0.55} & for\ \ \dfrac{w_l\delta z}{\cos\theta_s} \ge 0.01 kg/m^2 \end{cases}, \tag{6-18}$$

and $$a_w = k_a w_l,$$ (6-19)

where θ_s [radian] is the solar zenith angle. Coefficients k_r and k_a are expressed as

$$k_r = \min\left(\frac{1.7\times10^2 W_l}{\cos\theta_s}, 2\left(\frac{W_l}{\cos\theta_s}\right)^{-0.8}, 0.6\right),$$ (6-20)

$$k_a = \begin{cases} \dfrac{2.7\times10^2 W_l}{\cos\theta_s} & for \quad \dfrac{W_l}{\cos\theta_s} < 6.3\times10^{-3} \\ a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0 & for \quad 6.3\times10^{-3} \le \dfrac{W_l}{\cos\theta_s} < 0.1, \\ 1.5\left(\dfrac{10W_l}{\cos\theta_s}\right)^{-0.8} & fot \quad 0.1 \le \dfrac{W_l}{\cos\theta_s} \end{cases}$$ (6-21)

$$W_l = \int_{z_g}^{H}\left(\rho w_f + \frac{P_r}{V_f}\right)dz,$$ (6-22)

and $$x = \log\frac{W_l}{\cos\theta_s},$$ (6-23)

where ρ [kg m^{-3}] is the air density, w_f [kg m^{-3}] is the fog water content calculated in the atmosphere sub-model, P_r [kg m^{-2} s^{-1}] is the precipitation intensity in the canopy calculated in the vegetation sub-model, V_f [m s^{-1}] is the vertical speed of raindrop, and constants a_0, a_1, a_2, a_3, and a_4 have values 0.2420, -0.3135, 0.1871, -1.406, and -0.6491.

6.3 Projection Coefficients

Projection coefficients k_d and k_s are determined geometrically from the leaf orientation (normal to the leaf surface) and the incident radiation angle by the geometrical method[35]. Here, a simple leaf orientation distribution called semi-uniform[35), 36)] is used. Leaf orientation of this type has the same zenith angle and random azimuth angle. The merit of this treatment is that the plant structure can be specified by only the profile of leaf area density and the zenith angle of leaf orientation. Angles used in the radiation scheme and the ways of scattering of radiation by leaves are illustrated in Fig. 6-1.

The angle Θ [radian] between the leaf orientation and the direction of the sun is given by

$$\cos\Theta = \cos\theta_l\cos\theta_s + \sin\theta_l\sin\theta_s\cos(\phi_l - \phi_s),$$ (6-24)

where θ_l and θ_s [radian] are zenith angles of leaf orientation and the sun, respectively, and φ_l and φ_s [radian] are azimuth angles of leaf orientation and the sun, respectively. Using this angle, the projection of the unit individual leaf area on the horizontal plane is expressed as $\cos\Theta/\cos\theta_s$. Since k_d is the mean value of this projection coefficient of leaves in a canopy layer, it is expressed by

$$k_d = \frac{\langle \cos\Theta \rangle}{\cos\theta_s}, \tag{6-25}$$

where $\langle\cos\Theta\rangle$ is the mean value of $\cos\Theta$ in the layer. There are three types of leaf orientation distribution, called uniform, semi-uniform, and heliotropism[35]. The uniform type has a uniform distribution of leaf orientation, that is, both zenith and azimuth angles have equal probabilities of pointing at any direction. The semi-uniform type has the same zenith angle and uniformly distributed azimuth angle. The heliotropism type changes leaf orientation in response to movement of the sun. Formulations for the first and second types are considered here. For the uniform type, $\langle\cos\Theta\rangle$ is given by

$$\langle \cos\Theta \rangle = \frac{1}{2\pi}\int_0^{2\pi}\int_0^{\pi/2} \left|\cos\Theta\right| \sin\theta_l d\theta_l d\phi_l . \tag{6-26}$$

By integrating this equation numerically, one obtains $\langle\cos\Theta\rangle = 1/2$. Therefore, k_d is determined only by the solar zenith angle and expressed as $k_d = 1/(2\cos\theta_s)$. For the semi-uniform type, $\langle\cos\Theta\rangle$ is calculated by

$$\langle \cos\Theta \rangle = \frac{1}{2\pi}\int_0^{2\pi} \left|\cos\Theta\right| d\phi_l . \tag{6-27}$$

In this equation, $\cos\Theta$ is given by (6-24) with a constant θ_l. The integration of (6-27) becomes

$$\langle \cos\Theta \rangle = \frac{2\phi_t - \pi}{\pi}\cos\theta_l \cos\theta_s + \frac{2\sin\phi_t}{\pi}\sin\theta_l \sin\theta_s, \tag{6-28}$$

where $\phi_t = \cos^{-1}\left(-\cot\theta_l \cot\theta_s\right)$ (6-29)

determines which side of leaf is illuminated by the direct solar radiation flux as shown in Fig. 6-1, and has a value $\varphi_t \leq \pi$. Also, $\varphi_t = \pi$ is used when ($-\cot\theta_l \cot\theta_s$) is negative. Therefore, k_d for this type is determined by θ_s and θ_l. The solar zenith angle can be given as a function of latitude of the calculation point and time. The zenith angle of leaf orientation needs to be prescribed as one of the vegetation parameters.

The coefficient k_s is derived by using the assumption that the diffuse radiation contains components from the whole hemispheric direction homogeneously. By defining the radiation flux intensity from a unit solid angle as S_0, the contribution of S_0 from the direction of zenith angle θ and azimuth angle φ to the downward radiation flux is expressed by $S_0\cos\theta$. The downward radiation flux S is given by the integration of S_0 for the whole hemisphere,

$$S = \int_0^{2\pi}\int_0^{\pi/2} S_0 \cos\theta \sin\theta d\theta d\phi = \pi S_0 . \tag{6-30}$$

The angle Θ between leaf orientation (θ_l, φ_l) and one particular direction of S_0 (θ, φ) is given by (6-24) by replacing (θ_s, φ_s) with (θ, φ). The radiation flux intensity of this component on a unit leaf surface is expressed as $S_0|\cos\Theta|$. By integrating this for the whole hemisphere, the radiation flux S_l on a unit leaf area with the leaf orientation (θ_l , φ_l) is calculated as

$$S_l = \int_0^{2\pi}\int_0^{\pi/2} S_0 \left|\cos\Theta\right| \sin\theta d\theta d\phi . \tag{6-31}$$

Similar to (6-26), this equation is integrated as $S_l = \pi S_0$ independent of leaf orientation. Therefore, the average projection coefficient of leaves for the diffuse radiation flux, k_s is unity.

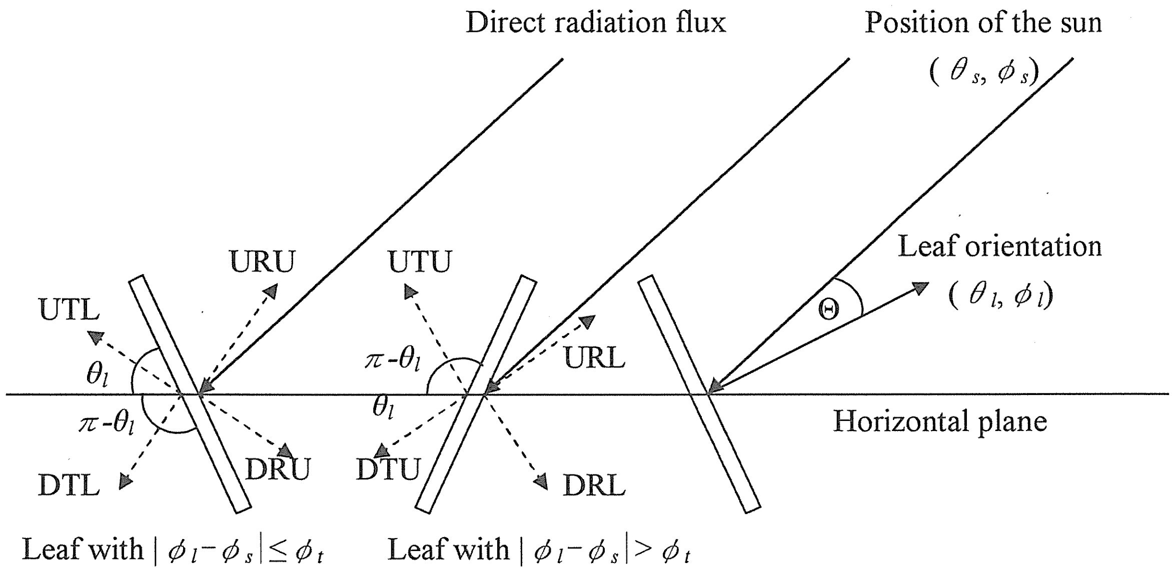

Fig. 6-1 Angles used in the new radiation scheme and the ways of scattering (reflection and transmission) of direct radiation flux. The abbreviations for scattering radiations (URU, DRU, etc.) are described in the text.

6.4 Scattering Coefficients

The scattering coefficients for the direct radiation flux, f_{df} and f_{db}, are determined by the geometrical method[36]. The reflection and transmission are considered as the scattering and each component is assumed to radiate homogeneously to each hemispheric direction bounded by the leaf surface. With this assumption, the distribution of the reflected and transmitted components into the downward and upward fluxes is determined by the zenith angle of the leaf orientation θ_l as

$$\left(F^{\downarrow}_{upper}, F^{\uparrow}_{upper}\right) = \left(F^{\uparrow}_{lower}, F^{\downarrow}_{lower}\right) = \left(\frac{\theta_l}{\pi}, \frac{\pi-\theta_l}{\pi}\right), \tag{6-32}$$

where $F^{\downarrow}$ and $F^{\uparrow}$ represent the portions of the reflected and transmitted components becoming the downward and upward diffuse radiation fluxes, respectively, and subscripts upper and lower express which side of the leaf the radiation comes from. The portion of the intercepted direct solar radiation illuminating upper and lower sides of leaves, R_{upper} and R_{lower}, respectively, for the semi-uniform type of leaf orientation distribution is expressed as

$$\left(R_{upper}, R_{lower}\right) = \left(\frac{\phi_t}{\pi}, \frac{\pi - \phi_t}{\pi}\right), \tag{6-33}$$

where φ_t is given by (6-29).

There are four paths through which the upward diffuse radiation flux is produced from the intercepted direct radiation by leaves as shown in Fig. 6-1: (i) the upward reflection from the upper side of leaf (URU) due to the illumination on the upper side of leaf, (ii) the upward transmission from the lower side of leaf (UTL) due to the illumination on the upper side of leaf, (iii) the upward reflection from the lower side of leaf (URL) due to the illumination on the lower side of leaf, and (iv) the upward transmission from the upper side of leaf (UTU) due to illumination on the lower side of leaf. Therefore, the backward scattering coefficient f_{db} is defined as the ratio of produced upward diffuse radiation to intercepted direct radiation flux by leaves, given by

$$f_{db} = \left(\frac{\pi - \theta_l}{\pi} A_r + \frac{\theta_l}{\pi} A_t\right)\frac{\phi_t}{\pi} + \left(\frac{\theta_l}{\pi} A_r + \frac{\pi - \theta_l}{\pi} A_t\right)\frac{\pi - \phi_t}{\pi}, \tag{6-34}$$

where A_r and A_t are the reflectivity and transmissivity of leaf surface, respectively. Similarly considering the production of downward diffuse radiation flux, the forward scattering coefficient f_{df} is given by

$$f_{df} = \left(\frac{\theta_l}{\pi} A_r + \frac{\pi - \theta_l}{\pi} A_t\right)\frac{\phi_t}{\pi} + \left(\frac{\pi - \theta_l}{\pi} A_r + \frac{\theta_l}{\pi} A_t\right)\frac{\pi - \phi_t}{\pi}. \tag{6-35}$$

The scattering coefficients for the diffuse radiation flux, f_{sf} and f_{sb} are also determined in the same way. A part of the downward diffuse radiation flux is scattered upward by leaves through the same four paths as the production of the upward diffuse radiation flux from the intercepted direct radiation flux by leaves. While the distribution of the scattered component into the downward and upward fluxes is determined by (6-32), the portions of the downward diffuse radiation flux intercepted by leaves illuminating the upper and lower sides of leaves are expressed as $(\pi - \theta_l)/\pi$ and θ_l/π, respectively, considering the isotropic radiation flux. By defining similarly as the scattering coefficients for the direct radiation flux, the backward scattered coefficient f_{sb} for the downward diffuse radiation flux is given by

$$f_{sb} = \frac{\pi - \theta_l}{\pi}\left(A_r \frac{\pi - \theta_l}{\pi} + A_t \frac{\theta_l}{\pi}\right) + \frac{\theta_l}{\pi}\left(A_r \frac{\theta_l}{\pi} + A_t \frac{\pi - \theta_l}{\pi}\right). \tag{6-36}$$

This coefficient is the same for the upward diffuse radiation flux. Similarly, the forward scattering coefficient for the diffuse radiation flux f_{sf} is expressed as

$$f_{sf} = \frac{\pi - \theta_l}{\pi}\left(A_r \frac{\theta_l}{\pi} + A_t \frac{\pi - \theta_l}{\pi}\right) + \frac{\theta_l}{\pi}\left(A_r \frac{\pi - \theta_l}{\pi} + A_t \frac{\theta_l}{\pi}\right). \tag{6-37}$$

7. Numerical Scheme

A finite difference scheme is used to solve the equations presented in Chapters 3 to 6. The definition of grid system is shown in Fig. 7-1. Vertical grid number (k) is expressed as a subscript with parentheses of variables. The expression ($k \pm 1/2$) means the middle point between grids. The number (k) is 0 at the ground surface, positive value for the upward direction, and negative value in soil. Grid number (k) is N_a at the top boundary and N_s (negative value) at the bottom. Time is expressed as a superscript with parentheses of variables. Super- and subscripts are omitted if they are not necessary.

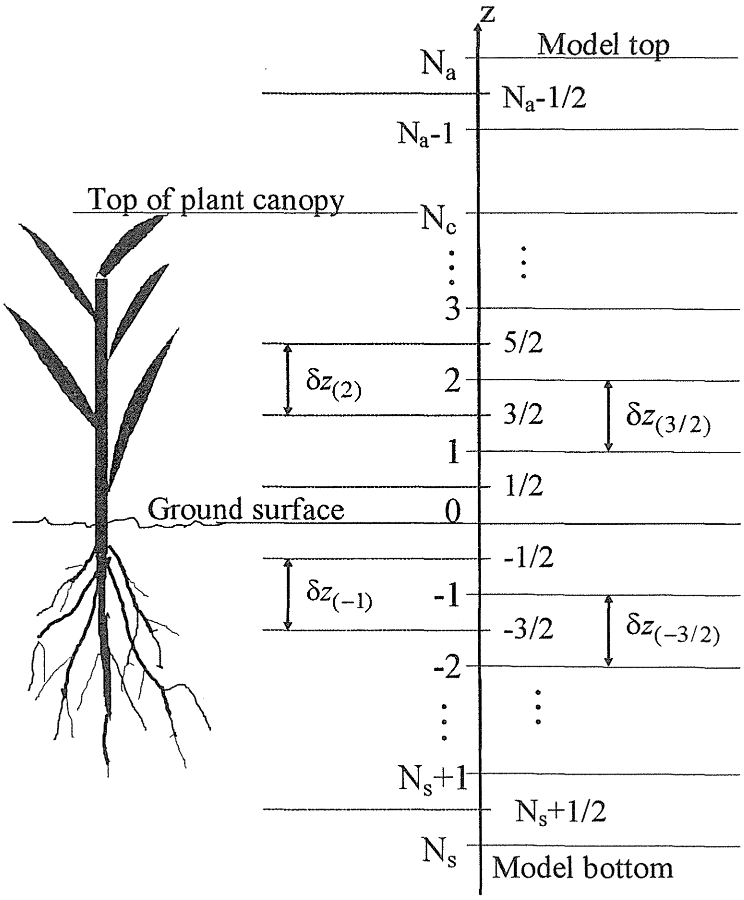

Fig. 7-1 Definition of vertical grid numbering system.

One-dimensional diffusion equation, which is included as a common part in most basic equations of the model, is generally expressed as

$$\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial z} K \frac{\partial \phi}{\partial z} + A\phi + F \,. \tag{7-1}$$

The finite difference expression for (7-1) is

$$\phi_{(k)}^{(t+\delta t)} - \phi_{(k)}^{(t)} = \delta t \left(\Delta_{(k)} + A_{(k)} \right) \left[\mu \phi_{(k)}^{(t+\delta t)} + (1-\mu) \phi_{(k)}^{(t)} \right] + \delta t F_{(k)} , \tag{7-2}$$

where μ is the parameter to determine the scheme: explicit scheme if $\mu = 0$, implicit scheme if $\mu = 1$, and Crank-Nicolson scheme if $\mu = 1/2$. The operator $\Delta_{(k)}$ expresses the finite differential for diffusion terms as

$$\Delta_{(k)}\phi = \delta_{k+}\left(\phi_{(k+1)} - \phi_{(k)}\right) - \delta_{k-}\left(\phi_{(k)} - \phi_{(k-1)}\right), \quad (7\text{-}3)$$

$$\delta_{k+} = \frac{\delta t K_{(k+1/2)}}{\delta z_{(k)} \delta z_{(k+1/2)}}, \quad (7\text{-}4)$$

$$\delta_{k-} = \frac{\delta t K_{(k-1/2)}}{\delta z_{(k)} \delta z_{(k-1/2)}}, \quad (7\text{-}5)$$

and $$\delta z_{(k)} = z_{(k+1/2)} - z_{(k-1/2)}. \quad (7\text{-}6)$$

By rearranging (7-2) with respect to $\varphi^{(t+\delta t)}$, simultaneous equation system for $\varphi^{(t+\delta t)}$ is obtained. Its k-th equation is expressed as

$$\alpha_{k,k-1}\phi_{(k-1)}^{(t+\delta t)} + \alpha_{k,k}\phi_{(k)}^{(t+\delta t)} + \alpha_{k,k+1}\phi_{(k+1)}^{(t+\delta t)} = \gamma_k, \quad (7\text{-}7)$$

where $\alpha_{i,j}$ is the (i,j)-component of coefficient matrix, which is a triple diagonal matrix. Except for the boundaries (k=0, 1, N or N_S), components of the matrix are expressed as

$$\alpha_{k,k-1} = -\mu\delta_{k-}, \quad (7\text{-}8)$$

$$\alpha_{k,k} = 1 - \mu A \delta t - \alpha_{k,k-1} - \alpha_{k,k+1}, \quad (7\text{-}9)$$

$$\alpha_{k,k+1} = -\mu\delta_{k+}, \quad (7\text{-}10)$$

and $$\gamma_k = \phi_{(k)}^{(t)} + (1-\mu)\delta t \Delta_{(k)}\phi^{(t)} + (1-\mu)A_{(k)}\delta t \phi_{(k)}^{(t)} + \delta t F_{(k)}. \quad (7\text{-}11)$$

The solutions of the simultaneous equations are obtained by Gaussian elimination methods. The forward elimination yields from

$$\phi_{(k)}^{(t+\delta t)} + \alpha'_{k,k-1}\phi_{(k-1)}^{(t+\delta t)} = \gamma'_k, \quad (7\text{-}12)$$

where $$\alpha'_{k,k-1} = -\frac{\alpha_{k,k-1}}{\alpha_{k,k} - \alpha_{k,k+1}\alpha'_{k+1,k}}, \quad (7\text{-}13)$$

and $$\gamma'_k = -\frac{\gamma_k - \alpha_{k,k+1}\gamma'_{k+1}}{\alpha_{k,k} - \alpha_{k,k+1}\alpha'_{k+1,k}}. \quad (7\text{-}14)$$

Initial values for the forward elimination are expressed as

$$\alpha'_{2,1} = \frac{\alpha_{2,1}}{\alpha_{1,1}}, \tag{7-15}$$

and $$\gamma'_1 = \frac{\gamma_1}{\alpha_{1,1}}, \tag{7-16}$$

for equations in the atmosphere, and

$$\alpha'_{0,-1} = \frac{\alpha_{0,-1}}{\alpha_{0,0}}, \tag{7-17}$$

and $$\gamma'_0 = \frac{\gamma_0}{\alpha_{0,0}}, \tag{7-18}$$

for those in the soil.

For the advection term of CO_2 transport in the soil, the low-numerical diffusion scheme HIFI[58)] is used. This method is a hybrid of a new interpolation scheme FI method, the first-order upwind, and second-order upwind schemes. The FI method is designed so as to maximize the accuracy without loosing the stability through the use of linear analysis[58)].

8. Coupling with Atmosphere Model

To couple an atmosphere model and a land-surface model, it is general to make a single model code by incorporating the land-surface model into the atmosphere model. However, a totally different way of the model coupling is proposed[56]. A non-hydrostatic atmospheric dynamic model of Pennsylvania State University and National Center for Atmospheric Research (PSU/NCAR-MM5)[27] is used as the atmosphere model coupled with SOLVEG2. MM5 and SOLVEG2 calculations are carried out as independent tasks for different processors, and their coupling is achieved by exchanging their outputs as MPI communication between processors as shown in Fig. 8-1. This type of parallel calculation is called MPMD.

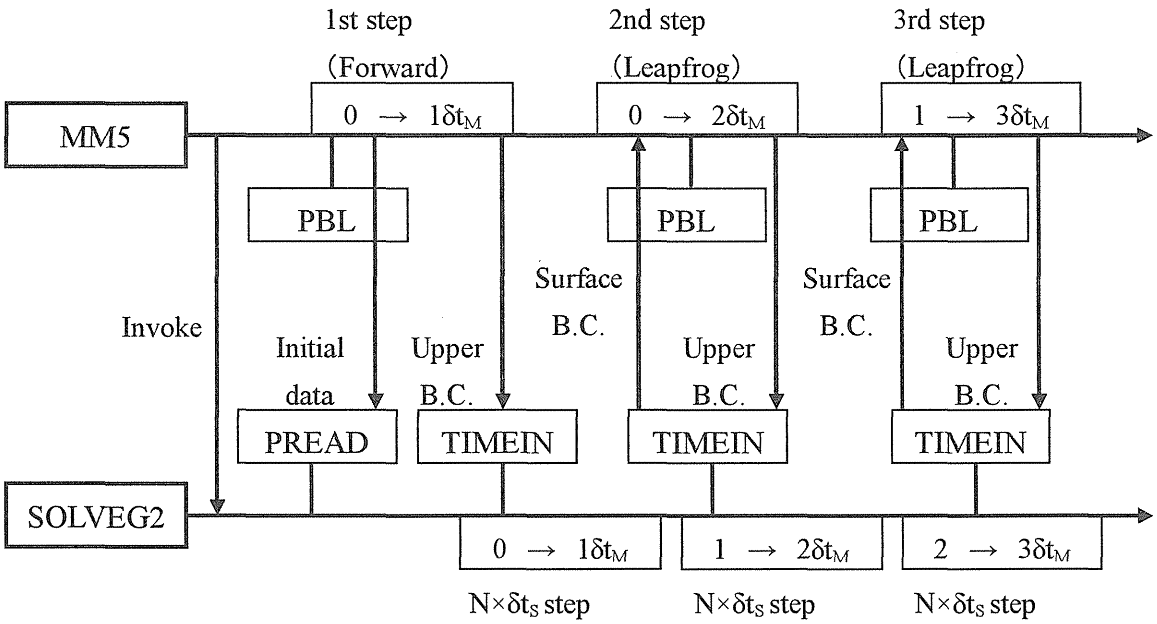

Fig. 8-1 Data exchanges between coupled models. PREAD and TIMEINT represent the SOLVEG2 routines for the initial and boundary conditions, respectively. The parameters δt_M and δt_S are time increments of MM5 and SOLVEG2 calculations, respectively.

MM5 calculation starts at first. Then, it invokes SOLVEG2 calculation in its initialization processes. After the PBL calculation in the first time step of MM5 time integration, MM5 processor sends SOLVEG2 the initial values and the first boundary conditions for SOLVEG2: air pressure, radiation, precipitation, wind speed, temperature, humidity, etc, which are mostly calculated in PBL calculation. With these inputs, SOLVEG2 calculation proceeds for the same time interval as MM5 and sends its results to MM5: skin temperature, surface heat and vapor fluxes, and albedo. MM5 receives these values before PBL calculation in the next time step and uses them as the land-surface boundary conditions for the PBL process. After PBL calculation, MM5 sends SOLVEG2 the top boundary condition for SOLVEG2 for the next time step, and the same cycle of processes are carried out repeatedly until the end of calculation. The time step of SOLVEG2 calculation is usually smaller than that of MM5, and several time steps are carried out for SOLVEG calculation during a single time step of MM5 calculation.

This coupling method is flexible and allows us to use the nesting functions of MM5. Figure 8-2 shows the flow of coupling calculation and data exchanges for two-domain, two-way nesting calculation. MM5 nesting calculations for outer and inner domains (dom. 1 and dom. 2 in Fig. 8-2, respectively) are carried out successively in one time step of the outer domain, and three time step for the inner domain in this procedure. On the other hand, SOLVEG2 calculations for large and local domains (dom.1 and dom. 2 in Fig. 8-2, respectively) are processed as independent tasks by different processors. Data exchanges between corresponding domains of MM5 and SOLVEG2 take place independently. This method is also applicable to more complex nesting domains.

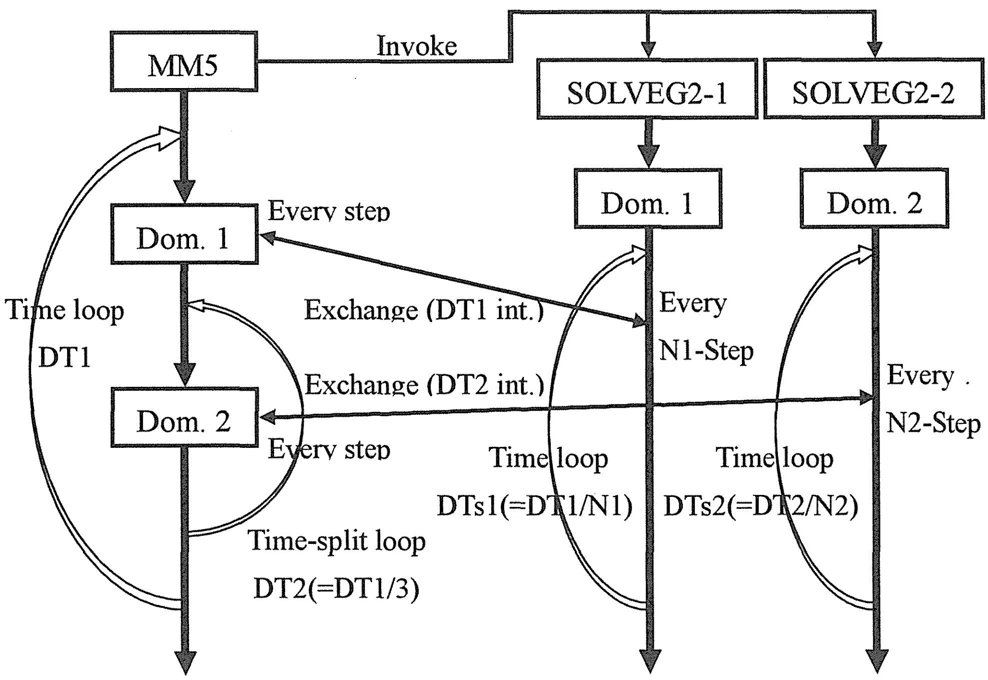

Fig. 8-2 Data exchanges for nesting calculations. Parameters DT1/2 and DTs1/2 represent time increments of MM5 and SOLVEG2 for Domain-1/2, respectively.

This coupling method also has flexibility in use of parallel computers, by adopting the Stampi[57] as the MPI library. While the MPI usually establishes communications among processors in a single parallel computer, JAERI has developed the advanced version of MPI, Stampi, to achieve the communication between different parallel machines. The utilization of the Stampi for the MPI library in the coupling programs allows us to execute two models on different computers. By executing two models on different computers, the load balance of different computers. By executing two models on different computers, the load balance of calculations for two models can be optimized. MM5 usually has higher computational cost than SOLVEG2, and its program code is vectorized as well as parallelized. Therefore, the combination of computers with different spec, for example, a vector parallel computer for MM5 and scalar parallel computer for SOLVEG2, is effectively used to execute this coupling model.

The modification of each model code for this coupling is simple and easy, just adding some data exchange routines and put some sentences in the original model code that call the routines. Each model code can keep its original structure. Therefore, we can use compile options, namelist, shell-script, and input dataset of each model in their original form. Details of the data exchange routines and modification of each model are described in the following section. This coupling method also has flexibility to use different resolution of grid for each model by interpolating one model's data to the other model's grid.

9. Model Code

The model code is written in FORTRAN77 and executable on UNIX-OS. The model has a function of parallel calculation by MPI. Test calculations have been done on Fujitsu parallel computer Primepower. Moreover, the model outputs can be visualized by using the Numerical Environment System SPEEDI-MP[59], which is the numerical experiment tool for environmental studies. In this chapter, details of the model code and procedure to run the model are described.

9.1 Structure of Model Code

a. Directories and Files

In SOLVEG root directory, there are the model source code directory (SRC), one-dimensional calculation input data directory (INPUT), three-dimensional calculation input data directory (INPUTx), point data output directory (OUTPUT), grid data output directory (GRIDOUT), and coupling module for the atmosphere model MM5 (MM5). Files in each directory are as follows.

1) Root Directory: SOLVEG/

- NQS shell-scripts	go_xxx.sh
- Executables	zsolveg_xxx.exe
- Parameter files	param_xxx

where xxx represents 1D (for one-dimensional calculation), 3D (for three-dimensional calculation), 3Dmpi (for three-dimensional parallel calculation), and couple1, 2 or 3 (for coupling calculation with the atmosphere model MM5).

2) Source Code Directory: SOLVEG/SRC/

- Make shell-scripts	zmake_xxx
- Makefiles	zmakefile_xxx
- Include files	Incl*
- Program files	*.f
- Horizontal grid file	zmesh.grid_3D
- Vertical grid files	zmesh.model_1D/3D
- Soil parameter file	zsoil.table
- Vegetation profile files	zvege.profile_1D/3D
- Vegetation parameter files	zvege.table_1D/3D
- NetCDF output parameter file	nc.template

where NetCDF is the network Common Data Form proposed by Unidata (http://my.unidata.ucar.edu/content/software/netcdf/index.html). This data format is used in the Numerical Environment System SPEEDI-MP.

3) 1-D Calculation Input Directory: SOLVEG/INPUT/

- Meteorology data file metdata.dat

where this file include all input meteorology data as shown in Table 9-1.

Table 9-1 Meteorology data file for 1-D calculation: metdata.dat.

TIME	P	RS	RL	RR	U	V	T	Q	CO2
1997-04-20_0015	964.36	108.28	317.14	0.00	-1.79	2.86	293.01	6.93	370.00
1997-04-20_0045	964.53	24.64	313.94	0.00	-1.75	2.41	291.96	6.81	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}], CO2: CO_2 concentration [ppmv].

4) 3-D Calculation Input Directory: SOLVEG/INPUTx/

There are sub-directories for meteorology data (METDATA) and parameters (PARAMETER).

In SOLVEG/INPUTx/METDATA/,

- Surface pressure files [hPa] pressure/PRyyyy-mm-dd_hhmm
- Solar radiation files [W m^{-2}] sw_down/SWyyyy-mm-dd_hhmm
- Long-wave radiation files [W m^{-2}] lw_down/LWyyyy-mm-dd_hhmm
- Wind u-component files [m s^{-1}] u_wind/UWyyyy-mm-dd_hhmm
- Wind v-component files [m s^{-1}] v_wind/VWyyyy-mm-dd_hhmm
- Air temperature files [K] air_temp/TAyyyy-mm-dd_hhmm
- Specific humidity files [g kg^{-1}] spec_humidity/QHyyyy-mm-dd_hhmm
- Rain intensity files [mm h^{-1}] precip/RAyyyy-mm-dd_hhmm
- CO_2 concentration files [ppmv] co2/CCyyyy-mm-dd_hhmm

In SOLVEG/INPUTx/PARAMETER/,

- Land-use data file [1 to 24, USGS land type] LANDUSE.dat
- Initial soil water content file [m^3 m^{-3}] SMOIST.dat
- Soil type file [1 to 16, Soil type in SOLVEG] SOILTX.dat
- Deep soil temperature file [K] TBSOIL.dat
- Sea surface temperature file [K] TSEASFC.dat
- Ground elevation file [m] ght.dat
- Grid latitude file [deg.] lat.dat
- Grid longitude file [deg.] lon.dat
- Air density file [kg m^{-3}] rou.dat

where yyyy-mm-dd_hhmm represents the year, month, day, hour, and minutes in the universal time constant UTC. Each file includes two-dimensional grid data.

5) Point Data Output Directory: SOLVEG/OUTPUT/

- Standard output files (fu06)	outlist (outXXX: XXX=MPI_RANK)
- Atmospheric variable file (fu20)	dbout
- Input meteorological data file (fu23)	METout
- Surface flux file (fu24)	FLXout
- Wind speed file (fu25)	WNDout
- Atmospheric CO_2 file (fu26)	ACO2out
- Atmospheric CO_2 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 CO_2 file (fu50)	SCO2out
- Canopy CO_2 file (fu51)	VCO2out
- Soil CO_2 production file (fu52)	PSCO2out
- Soil CO_2 budget file (fu53)	BSCO2out

where these files include one-dimensional vertical profiles or point values. In three-dimensional calculation, values at one grid point that is defined in the source code (IX, IY in Inclnum) are outputted.

6) Grid Data Output Directory: SOLVEG/GRIDOUT/

- GrADS control file	grads.ctl
- GrADS output files	grads/Tyyyy-mm-dd_hhmm
- NetCDF parameter file	nc.nmlist
- NetCDF output files	netcdf/solvegyyyy-mm-dd_hhmm.nc

where GrADS is the Grid Analysis and Display System (http://www.iges.org/grads/).

7) Coupling Module: SOLVEG/MM5/

For the coupling with the atmosphere model MM5, a coupling program file (couple_solveg.F) and some modified MM5 code are included. After setting up the MM5 code, unfold a TAR file in this directory (COUPLING.TAR) on the MM5 compile directory, and the coupling program and modified MM5 code are installed. These programs are applicable to the latest (in July 2004) MM5 version MM5V3.6.3.

b. Source Code Files

The model source code consists of include files, program files, model setting files, parameter files, and make files in the source directory (SOLVEG/SRC/). Brief explanation of include and program files are described in this section, since other files are described in the previous section.

1) Include Files

- Inclcon1	Common blocks for constants and input meteorological data
- Inclcon2	Common blocks for constants defined in BLOCKDATA
- Inclnum	Parameters for grid numbers
- Inclnum_xxx	Inclnum files for 1-D and 3-D calculations
- Inclvari	Common blocks for variables

2) Program Files

- 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 and 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
- 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_xxx	gzsolveg.f files for 1-D and 3-D calculations
- main.f	Main routine SOLVEG2
- main.f_xxx	main.f for 1-D, 3-D, 3-D MPI parallel, and coupling calculations

- mcouple_mm5.f	Coupling routines STAMPI_START_M, STAMPI_END_M, REC_KILL_SIG_M, STAMPI_MKSEND_M, STAMPI_EXCHANGE1_M, and STAMPI_EXCHANGE2_M
- mpgather.f	Subroutines MPGATHER4 and MPGATHER8: parallel data gather
- ncout.f	Subroutine NCOUT: NetCDF file output
- ncout.f_xxx	ncout.f files for 3-D and 3-D MPI parallel calculations
- 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
- pgradsout.f	Subroutine PGRADSOUT: GrADS file output
- pgradsout.f_xxx	pgradsout.f files for 3-D and 3-D MPI parallel calculations
- pinit01.f	Subroutine MSHINT: atmosphere grid
- pinit01.f_xxx	pinit01.f files for 1-D and 3-D calculations
- 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_xxx	ppread.f files for 1-D, 3-D, and coupling calculations
- ptint.f	Subroutine TIMEINT: boundary data
- ptint.f_xxx	ptint.f files for 1-D, 3-D, and coupling 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
- solveg.f_xxx	solveg.f files for coupling and offline calculations
- 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
- 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
- svtemp.f	Subroutine VTEMP: vegetation temperature

c. Calculation Flow and Subroutines

The calculation flow of SOLVEG2 is shown in Fig. 9-1. Subroutines are categorized in to a hierarchy; the primary routines called by the main routine, secondary routines called by the primary routines, common routines, and functions. In Appendix, functions and in/output variables of routines are described according to this category except for the routines to couple with atmosphere model MM5, which are categorized as the coupling routines.

```
*******************************************************************************************
Main     | Primary          | Secondary       | Common routines| Functions and libraries
-------------------------------------------------------------------------------------------
SOLVEG2
 Start
   ├──────────────────────────────────────────────┬────── (MPI_INIT*)
   |                                              ├────── (MPI_COMM_SIZE*)
   |                                              └────── (MPI_COMM_RANK*)
   ├─── STAMPI_START_M ───────────────────────────┬────── (MPI_COMM_SIZE*)
   |                                              ├────── (MPI_COMM_RANK*)
   |                                              └────── (MPI_COMM_GET_PARENT*)
   ├─── PREAD     ──────── STAMPI_EXCHANGE1_M ────┬────── (MPI_RECV*)
   |                                              └────── (MPI_BCAST*)
   ├─── MSHINT
   ├─── SLVGIN     ┬───────────────────────────────────── SHMD
   |               ├────── GZSOLVEG
   |               ├────── GTABLE
   |               ├────── GVTABLE
   |               └────── GVPROFILE
   ├─── INITPF    ┬────────────────────── PCAL
   |               └────── CLSL2A
   ├─── FLXCAL
   ├─── SFPR13    ─────────────────────────────────────── PSYM, PSYH
   ├─── DEBUGW
Time loop start
  ┌─┐
  ↑ ├── TIMEINT   ┬────── STAMPI_EXCHANGE2_M ─────┬────── (MPI_SEND*)
    |             |               |               ├────── (MPI_RECV*)
    |             |               |               └────── (MPI_BCAST*)
    |             |               └────── MPGATHER4┬───── (MPI_RECV*)
    |             |                                └───── (MPI_SEND*)
    |             ├────────────────────── DEWTMP ──────── SHMD
    |             └────────────────────── PCAL
    ├── KMHCAL
    ├── FLXCAL
    ├── SOLVEG    ┬────────────────────────────────────── PSYM, PSYH, SHMD, FL, FCPAIR
    |             ├────────────────────── DEWTMP ──────── SHMD
    |             ├────── GVPROFILE
    |             ├────── SFCRAD     ┬────── RADIATION
    |             |                  └────── EPPARA
    |             ├────── SVAPO      ┬─────────────────── FDENSA, SHMD, FL
    |             |                  ├────── EVPARA
```

Continued on the following page.

```
 |              |              ├------- EHWS
 |              |              └------- SOLV1
 |              ├------ SLIQU  ┬------- EWPARA
 |              |              └------- SOLV2
 |              ├------ STEMP  ┬----------------------- FCPAIR, FCW, FL
 |              |              ├------- ESPARA  -------- FCW
 |              |              ├------- EALBED
 |              |              └------- SOLV1
 |              ├------ SLCO2  ┬------- EHWS
 |              |              ├------- HIFI1
 |              |              └------- SOLVE2
 |              ├------ RSCO2  ------------------------ SHMD
 |              ├------ RESISTS ----------------------- SHMD
 |              ├------ VLIQU  ┬----------------------- SHMD
 |              |              └------- EPPARA
 |              └------ VTEMP  ┬----------------------- FCPAIR, FCW, FL, SHMD, SHMDD
 |                             └------- EPPARA
 ├-- STAMPI_MKSEND_M
 ├-- SFPR13  ------------------------------------------ PSYM, PSYH
 ├-- UMAIN   -----------------┬------------------------ PSYM
 |                            ├------- GENER
 |                            └------- DIREC2
 ├-- TMAIN   -----------------┬------------------------ PSYM, PSYH, SHMD, FCPAIR, FL
 |                            ├------- GENER
 |                            ├------- DIREC2
 |                            └------- ELI2VA  -------- SHMD, SHMDD
 ├-- EMAIN   -----------------┬------------------------ FAIM
 |                            ├------- GENER
 |                            └------- DIREC1
 ├-- CMAIN   -----------------┬------------------------ PSYM, PSYH
 |                            ├------- GENER
 |                            └------- DIREC2
 ├-- SAVEOD
 ├-- DEBUGW
 ├-- GRADSOUT ----------------------- MPGATHER4┬------- (MPI_RECV*)
 |                                             └------- (MPI_SEND*)
 ├-- NCOUT   -----------------┬-----------------┬------ (netCDF_create**)
 |                            |                 ├------ (netCDF_put_comm**)
 |                            |                 ├------ (netCDF_put**)
 |                            |                 └------ (netCDF_close**)
↑ |                           └------ MPGATHER4┬------- (MPI_RECV*)
└─┘                                            └------- (MPI_SEND*)
Time loop end
   ├--- STAMPI_END_M---- REC_KILL_SIG_M ----------┬------ (MPI_RECV*)
   |                                              └------ (MPI_SEND*)
   ├----------------------------------------------------- (MPI_FINALIZE*)
 Stop
************************************************************************************************
```

Fig. 9-1 Calculation flow of SOLVEG2 coupled with MM5. Routines with single asterisk are ones in MPI library, and those with double asterisk are access routines in the Numerical Environmental System SPEEDI-MP, which provide the functions to output NetCDF files for the system.

9.2 Procedure to Run the Model

a. Compiling the Model Code

After setting the model grid, the compilation of the model code is took place. These procedures are as follows.

1) Model Grid Setting

The include files Inclnum_xxx and vertical grid files zmesh.model_1D/3D need to be modified if a different grid to the original setting is necessary. These files for one-dimensional calculation are shown in Tables 9-2 and 9-3. In the original model setting, numbers of the atmosphere, soil, and canopy layers are M1 = 9, NS = 7, and NC = 9, respectively. The canopy layers are common to the lower atmosphere layers. The horizontal grid numbers NX (x-direction) and NY (y-direction) and the point output grid IX and JY are all 1 for one-dimensional calculation. The parameter NA is the layer number for atmospheric variables output (layer of 1.5 to 3.0 m in this case).

Table 9-2 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 )
```

Table 9-3 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
```

2) Compile

In the source directory (SOLVEG/SRC/), run the make shell-script (zmake_xxx) to compile and link source code, and the executable (zsolveg_xxx.exe) is made in the root directory (SOLVEG/). The NetCDF output function can be used only on the computers connected to the Numerical Environment System SPEEDI-MP. For other computers, some modification is necessary to exclude the NetCDF output function. One is to comment out the call-sentence for the routine NCOUT in the main routine (main.f_xxx). Another is to delete the include path for NetCDF (NCDIR, INCDIR, LDFLAGS) and the NetCDF module (ncout.o) in the makefile (zmakefile_xxx), which is shown in Table 9-4. Since the

NetCDF output is the function for the grid output, it is used in one-dimensional calculation.

Table 9-4 Makefile for three-dimensional calculation: zmakefile_3D.

```
################################################################
#       Make file for Compiling solveg source
#       2004.06.20 by Nagai
################################################################
#
# Definition of macro
optv= -O2 -KV8PLUS
NCDIR = /…/netcdf-3.5.0
INCDIR = $(NCDIR)/include
LDFLAGS = -L/…/access2003 -lAccess2003 -L$(NCDIR)/lib -lnetcdf
# End of macro
#
zsolveg.go : efalbedo.o ehws.o     espara.o   evpara.o   ewpara.o    ¥
             eli2va.o   eppara.o                                    ¥
             faipsy.o   fcpair.o   fcw.o      fdensa.o   fl.o        ¥
             gtable.o   gvtable.o  gzsolveg.o gvprofile.o            ¥
             pblkd01.o  pdebugw0.o pfluxcal.o pgener.o               ¥
             pinit01.o  pinitpf.o  pmain03.o  ppread.o   sradiatn.o ¥
             main.o     ppcal.o    ptint.o    pgradsout.o            ¥
             sliqu.o    solver1.o  solver2.o  stemp.o    svapo.o     ¥
             srad.o     svliqu.o   svtemp.o   svrsco2.o  svrsst.o    ¥
             slco2.o    shifi1.o   solveg.o   ncout.o
        frt $(optv) -o zsolveg.go *.o $(LDFLAGS)
.f.o:
        frt -c $(optv) -fw -I$(INCDIR) $*.f
```

b. Execution

Before the model execution, input files and parameter files need to be prepared. These procedures are described here.

1) Input files

All input files in the input directory (SOLVEG/INPUT/ or INPUTx/) need to be prepared before the model execution. For time series data (meteorology data), the whole calculation period must be covered as shown in Table 9-1. Also, the vegetation profile file (zvege.profile_1D/3D: Table 9-5) in the source directory (SOLVEG/SRC/) 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 for each vegetation type need to be specified. The vegetation type is chosen from the vegetation parameter file (zvege.table_1D/3D), which is specified by two integers; the first number represents the category of vegetation, and the second shows the spatial or temporal variation in the category.

Table 9-5 Vegetation profile file for 1-D calculation: zvege.profile_1D.

```
***** DATA FORMATT ***********************************************************
*  yymmdd hrmnsc : DATE AND TIME -----------------------------------+ repeat  *
*   N : NUMBER OF LANDUSE CATEGORIES                                |         *
*   N1 / LANDUSE --------------------------------+ repeat N times   |         *
*   VTYPE(K),K=1,NC : NO in zvege.tabele         |                  |         *
*   AZ(K),K=1,NC    : leaf area density          |                  |         *
*   L : NUMBER OF ROOT : number of different VTYPE |                |         *
*   V1 RZ(K,V1),K=1,NS -------+ repeat L times   |                  |         *
*     .....                                      |                  |         *
*                                                |                  |         *
*  ---END OF THIS LANDUSE CATEGORY ---------------+                 |         *
*   N2 / LANDUSE                                                    |         *
*     .....                                                         |         *
*                                                                   |         *
*  ***END OF THIS TIME ---------------------------------------------+         *
*  yymmdd hrmnsc : DATE AND TIME                                              *
*     .....                                                                   *
*                                                                             *
***** DATA FORMATT ***********************************************************
!!!!! DATA START !!!!!
970420 001500 : DATE AND TIME
 1 : NUMBER OF LANDUSE CATEGORIES
 1 / WINTER WHEAT FIELD of CASES97
      41      41      41      41       0       0       0       0       0       0
   8.000   8.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000
 2 : NUMBER OF ROOT
   0   0.000   0.000   0.000   0.000   0.000   0.000   0.000
  41   0.000   0.150   0.250   0.500   0.100   0.000   0.000
---END OF THIS LANDUSE CATEGORY
***END OF THIS TIME
```

... repeat until the end time of the calculation period

2) Parameter file

In the parameter file (param_xxx), the calculation conditions such as calculation period, output interval, etc. are specified as shown in Table 9-6. In three-dimensional calculation, parameters for each grid from input files are used instead of values in this file for ROU, TBOTOM, TWATER, FLON, FLAT, STYPE, UTYPE, SMOIST, and SFTEMP. Parameters for horizontal grid DX, X00, and Y00 are no meaning for one-dimensional calculations.

Table 9-6 Sample parameter file for 3-D calculation: parame_3D.

```
IPRINT    =          3600<========  ( 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      =   25.0000000000D+00     (C)       REFERENCE TEMPERATURE       *
TBOTOM    =   25.0000000000D+00     (C)       SOIL BOTTOM TEMPERATURE     *
TWATER    =   25.0000000000D+00     (C)       WATER TEMPERATURE           *
EMSVTY    =    0.9800000000D-00     (       ) EMMISSIVITY OF G. SFC.      *
ALBEDO    =    0.2000000000D-00     (       ) ALBEDO       OF G. SFC.     *
TURBID    =    0.1000000000D-00     ( )       TURBIDITY OF AIR            *
Z0        =    1.0000000000D-02     (M)       SURFACE ROUGHNESS (WIND)    *
ZT        =    1.0000000000D-03     (M)       SURFACE ROUGHNESS (TEMP)    *
DELT      =    5.0000000000D+00     (S)       TIME INCREAMENT (S)         *
LDATES    =   20020927<========     (Y4M2D2)  INITIAL DATE                *
LTIMES    =     000000<========     (H2M2S2)  INITIAL TIME (STD.T.)       *
TINTEGD   =    0.0000000000D+00     (DAY)     INTEGRATION PERIOD (DAY)    *
TINTEGH   =    1.0000000000D+00     (H)       INTEGRATION PERIOD (H)      *
TINTINP   = 3600.0000000000D+00     (S)       INPUT DATA INTERVAL (S)     *
FLON      =   40.0000000000D+00     (DEG)     LONGITUDE                   *
FLAT      =   22.0000000000D+00     (DEG)     LATITUDE                    *
STDLON    =    0.0000000000D+00     (DEG)     LON. of STANDARD TIME       *
STYPE     =    4.0000000000D+00     (       ) SOIL TEXTURE NUMBER         *
UTYPE     =    2.0000000000D+00     (       ) LANDUSE TYPE NUMBER         *
SMOIST    =    0.3000000000D+00     (M3/M3)   SOIL WATER CONTENT          *
SFTEMP    =  298.1600000000D+00     (K)       SOIL SURFACE TEMPERATURE    *
CO2AP     =    0.0000000000D+00     (ppm)     AIR CO2 CONCENTRATION +     *
CO2SI     = 5000.0000000000D+00     (ppm)     SOIL BOTTOM 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        =   45.0000000000D+03     (M)       HORI. GRID INTERVAL         *
X00       =-1080.0000000000D+03     (M)       X COORDINATE of SW-POINT    *
Y00       =-1080.0000000000D+03     (M)       Y COORDINATE of SW-POINT    *
```

3) Execution

The model execution is done by submitting the NQS shell-script (go_xxx.sh). Sample of the shell-script for three-dimensional MPI parallel calculation is shown in Table 9-7. In this file, calculation of the former version SOLVEG can be done by switching off the CO_2 exchange calculation with the parameter ifco2 = 0. For three-dimensional calculations, parameters for horizontal grid (after ### Set NetCDF grid output parameters) need to be specified to make the NetCDF parameter file (nc.nmlist) in the grid data output directory.

Table 9-7 Sample NQS shell-script for 3-D MPI parallel calculation: go_3Dmpi.sh.

```
#!/bin/csh -f
#########################################################
# Ver. 3: Grid calculation for whole grid
#########################################################
#@$-C  solveg    # program name
#@$-r  SOLgo     # batch request name
#@$-q  p3        # submit batch job class
#@$-lP 32        # MPI CPU number
#@$-lp 1         # OpenMP number
#@$-eo           # error output to standard output dev.
#########################################################

set hmdir=$HOME/SOLVEG
set srdir=${hmdir}"/SRC"
set indir=${hmdir}"/INPUT2"
set otdir=${hmdir}"/OUT3Dmpi"
set grdir=${hmdir}"/GRIDOUTmpi"

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

### Set NetCDF grid output parameters
set X_size  = 100
set Y_size  = 130
set Z_size  = 7
set project = 3         # 1:Mercator, 2:Polarstereo, 3:Lambert
set lonc    = 40.0      # Longitude of projection center
set latc    = 22.0      # Latitude  of projection center
set tlat1   = 60.0      # True latitude 1
set tlat2   = 30.0      # True latitude 2

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

#input files
setenv fu10 ${hmdir}/param_3D2
setenv fu13 ${srdir}/zmesh.grid_3D
setenv fu14 ${srdir}/zmesh.model_3D
setenv fu15 ${srdir}/zsoil.table
```

Continued on the following page.

```
setenv fu16 ${srdir}/zvege.table_3D
setenv fu17 ${srdir}/zvege.profile_3Dc
```

```
#output files
#---in pzroot.f
setenv fu20 ${otdir}/dbout
setenv fu23 ${otdir}/METout
setenv fu24 ${otdir}/FLXout
setenv fu25 ${otdir}/WNDout
setenv fu26 ${otdir}/ACO2out
setenv fu27 ${otdir}/BACO2out

#---in solveg.f
setenv fu30 ${otdir}/mnout
setenv fu31 ${otdir}/TSout
setenv fu32 ${otdir}/HWout
setenv fu33 ${otdir}/QSout
setenv fu34 ${otdir}/EBout
setenv fu35 ${otdir}/SFout

setenv fu40 ${otdir}/VGout
setenv fu41 ${otdir}/VWout
setenv fu42 ${otdir}/VTout
setenv fu43 ${otdir}/RADout

setenv fu50 ${otdir}/SCO2out
setenv fu51 ${otdir}/VCO2out
setenv fu52 ${otdir}/PSCO2out
setenv fu53 ${otdir}/BSCO2out

### make nc.nmlist
echo "&dim"                                            >! ${grdir}/nc.nmlist
echo ""                                                >> ${grdir}/nc.nmlist
echo "     d_name( 1)='X'     ,  d_size( 1)=$X_size,"  >> ${grdir}/nc.nmlist
echo "     d_name( 2)='Y'     ,  d_size( 2)=$Y_size,"  >> ${grdir}/nc.nmlist
echo "     d_name( 3)='Z'     ,  d_size( 3)=$Z_size,"  >> ${grdir}/nc.nmlist
echo "     d_name( 4)='ONE'   ,  d_size( 4)=1,"        >> ${grdir}/nc.nmlist
echo ""                                                >> ${grdir}/nc.nmlist
echo "&end"                                            >> ${grdir}/nc.nmlist
echo ""                                                >> ${grdir}/nc.nmlist
cat ${srdir}/nc.template                               >> ${grdir}/nc.nmlist
echo ""                                                >> ${grdir}/nc.nmlist
echo "&GLOBAL"                                         >> ${grdir}/nc.nmlist
echo ""                                                >> ${grdir}/nc.nmlist
echo "     model = 'SOLVEG',"                          >> ${grdir}/nc.nmlist
```

Continued on the following page.

```
echo "     projection = $project,"                     >> ${grdir}/nc.nmlist
echo "     lonc = $lonc,"                              >> ${grdir}/nc.nmlist
echo "     latc = $latc,"                              >> ${grdir}/nc.nmlist
```

```
echo "    true_lat1 = $tlat1,"                          >> ${grdir}/nc.nmlist
echo "    true_lat2 = $tlat2,"                          >> ${grdir}/nc.nmlist
echo ""                                                 >> ${grdir}/nc.nmlist
echo "    x='X',"                                       >> ${grdir}/nc.nmlist
echo "    y='Y',"                                       >> ${grdir}/nc.nmlist
echo "    z='Z',"                                       >> ${grdir}/nc.nmlist
echo ""                                                 >> ${grdir}/nc.nmlist
echo "    lon='LON',"                                   >> ${grdir}/nc.nmlist
echo "    lat='LAT',"                                   >> ${grdir}/nc.nmlist
echo ""                                                 >> ${grdir}/nc.nmlist
echo "&end"                                             >> ${grdir}/nc.nmlist

#go
cd ${hmdir}

echo ${otdir} >! EXpara_3Dmpi  # INPUT DATA PATH
echo ${indir} >> EXpara_3Dmpi  # INPUT DATA PATH
echo ${grdir} >> EXpara_3Dmpi  # GRID  DATA PATH
echo ${ifco2} >> EXpara_3Dmpi  # CO2 CALCULATION

setenv fu09 ${hmdir}/EXpara_3Dmpi

timex mpiexec -n 32 -nl 0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,
22,23,24,25,26,27,28,29,30,31 -mode limited zsolveg_3Dmpi.exe >& ${otdir}/outlis
t
/bin/rm EXpara_3Dmpi
```

10. Test Calculations

Test calculations of the model were carried out for one-dimensional calculation and grid calculation cases. For the one-dimensional case, measured data at a winter wheat field by the Cooperative Atmosphere-Surface Exchange Study (CASES-97)[18] were used. For the grid case, the coupling calculation with the atmosphere model MM5 was carried out for the seacoast desert area of south-west Saudi Arabia. This test was carried out as a preliminary study related to the greening project of this area. NCEP/NCAR reanalysis data (provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from the Web site at http://www.cdc.noaa.gov/) was used for the MM5 input.

10.1 One-dimensional Calculation

The performance of the model was examined using measured data obtained by the first CASES field program in 1997, CASES-97[18]. The surface station (station 7) at a winter wheat field is the best-equipped station with the National Center for Atmospheric Research (NCAR) Atmosphere-Surface Turbulent Exchange Research (ASTER) facility[60]. The CO_2 concentration and flux at 2 m above the ground were also measured at this station. The model used inputs from a grid data set[61] based on the CASES-97 observation. Calculation was carried out for the period of 32 days from 20 April to 21 May 1997, and the CPU time for this calculation was 70 sec. by the Fujitsu parallel computer Primepower.

Half-hour averaged measurements were used for comparisons with model calculations. These are the atmospheric variables at 2 m height: horizontal wind speed (U), temperature (T), and specific humidity (Q), surface and soil variables at 5 cm depth: skin temperature (TSK), soil temperature (TS) and water content (SW), and surface fluxes: net radiation (RN), ground heat flux (GH), sensible heat flux (SH), latent heat flux (LH), and CO_2 flux (FC). In these fluxes, SH, LH, and FC were measured at 2 m height by the eddy covariance method. The ground heat flux at the soil surface was calculated from the soil heat flux measured by heat flux plate and heat storage within the layer above the sensor. These data can be downloaded from the web page for CASES-97 data archive (http://www.atd.ucar.edu/rtf/projects/cases97/). The model settings for this test are schematically illustrated in Fig. 10-1. Although calculation period was 32 days, only a part (14 days from 3 to 16 May 1997) of the period is used for comparisons with observations. It is because the condition of CO_2 measurements was not good before and after this period and the soil water calculations agreed well with observations after the first rainfall on 2 May in the calculation period. Figure 10-2 shows comparisons between calculations and observations for surface fluxes: RN, GH, SH, LH, and FC. The model simulated these variables as well as others satisfactorily. These comparisons are well described in other papers[16), 17), 23)].

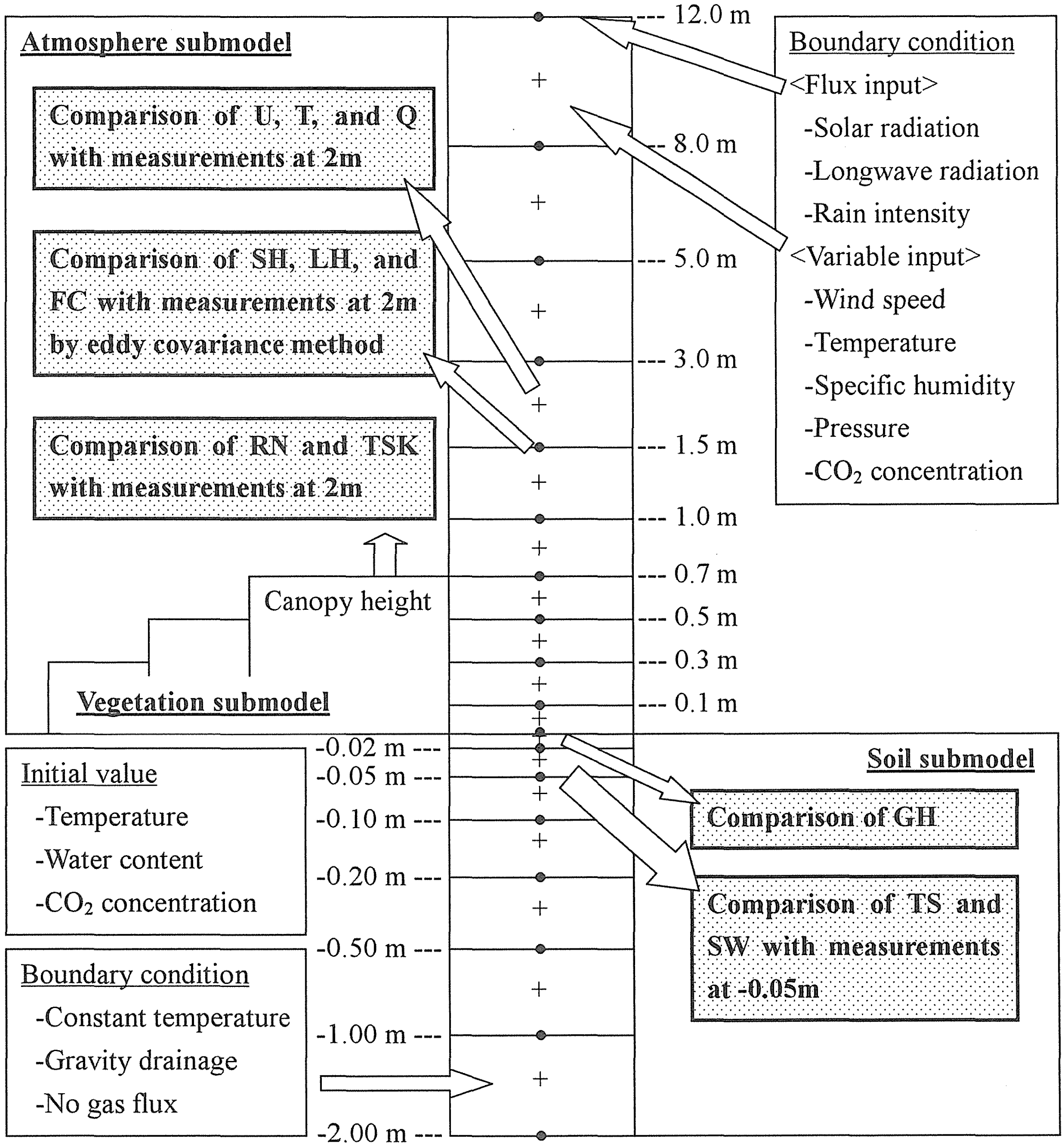

Fig. 10-1 Model settings for the performance test at the winter wheat field (station 7 of CASES-97, hear and in the following captions.). Ten and seven layers are used for the atmosphere and soil sub-models, respectively. The vegetation sub-model calculates only for the lower layers of the atmosphere below the canopy height (change from 0.3 to 0.7 m in the calculation period). In the model, variables and fluxes are calculated at the center (cross point) and boundary (dot point) of each layer, respectively.

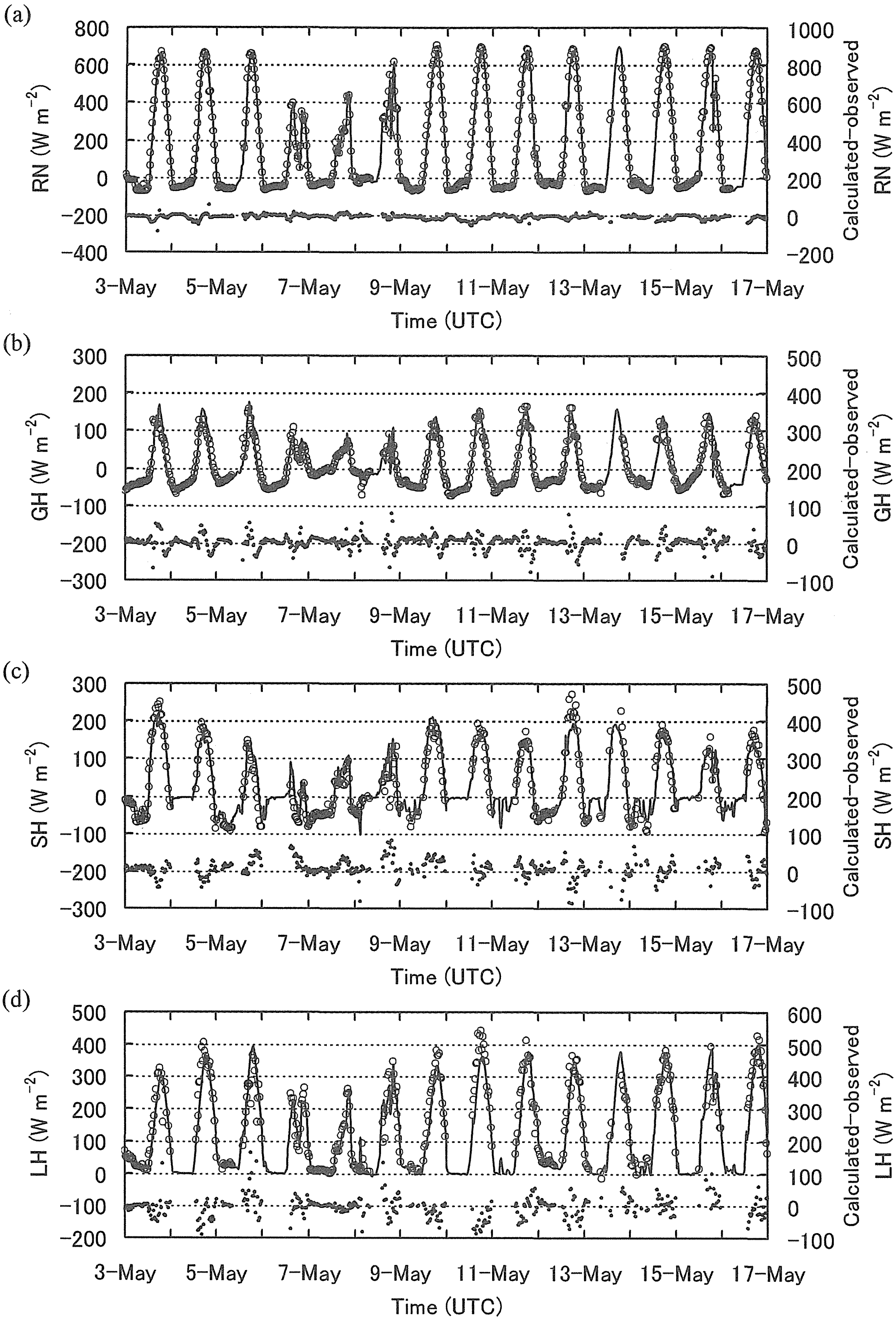

Fig. 10-2 Continued on the following page.

(e)

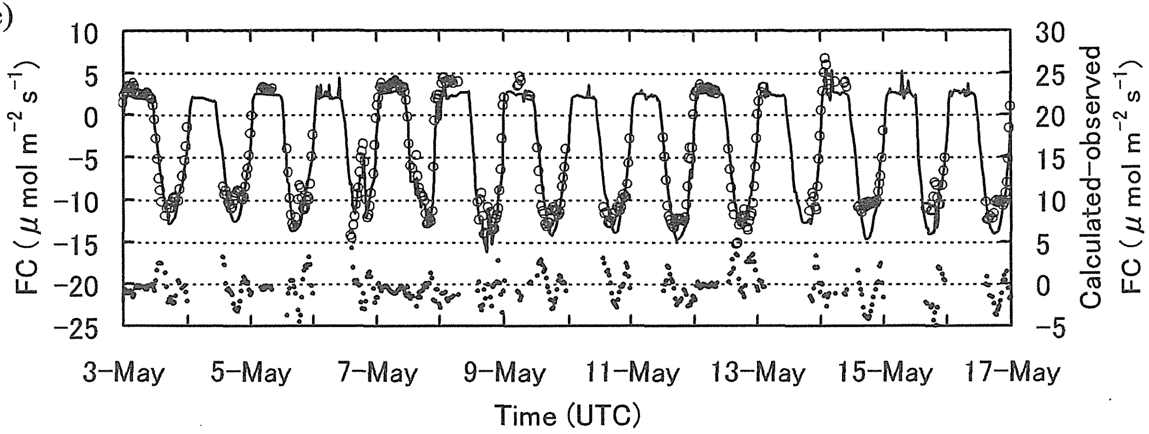

Fig. 10-2 Comparison between calculations (solid lines) and observations (open circles) for (a) net radiation RN, (b) ground heat flux GH, (c) sensible heat flux SH, (d) latent heat flux LH, and (e) CO_2 flux at the winter wheat field (station 7). Dots show the difference between calculations and observations.

10.2 Grid Calculations

The MM5-SOLVEG2 coupled calculations for two-domain, two-way nesting was carried out. Calculation domains are shown in Fig. 10-3. Input data and model settings are as follows:

Input data:

- NCEP/NCAR Reanalysis
- Resolution 2.5°×2.5°, 17 pressure levels
- Interval 6 hours (00, 06, 12, 18 UTC)

MM5 options:

- Cumulus Grell
- Microphysics Reisner2
- Radiation Cloud
- PBL MRF
- LSM OSU-LSM

MM5 domain 1:

- Area 4,500 km square
- Grid 100×100×23
- Resolution 45 km
- Time increment 90 s

MM5 domain 2:

- Area 1,500 km × 1,950 km
- Grid 100×130×23
- Resolution 15 km
- Time increment 30 s

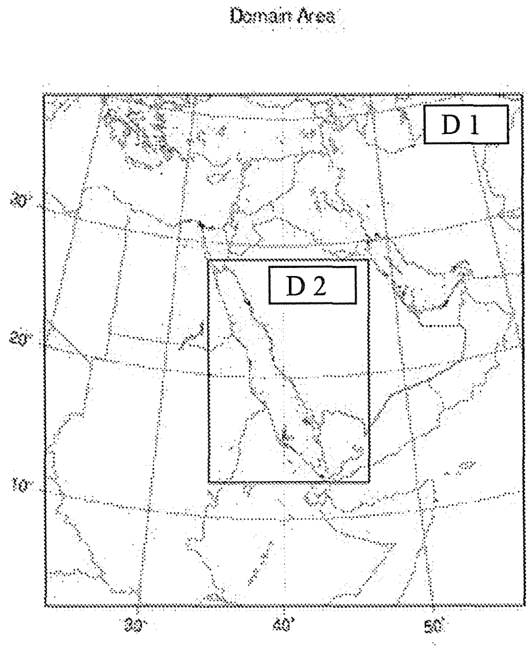

Fig. 10-3 Calculation domains.
D1: Domain1, D2: Domain 2.

SOLVEG2:

- Atmosphere 10 layers, 10 m above the surface
- Soil 7 layers, 2 m below the land surface
- Vegetation Lower 5 layers of atmosphere
- Time increment 5 s (both domains)
- Assumed land desert for all land-use

Calculation period:

- 3 days from 15 September 2003

As shown in Fig. 8-2, at least three processors (one for MM5, two for SOLVEG2 domains) are necessary for this case. The distributed memory parallel execution of MM5 (MPP) can be used in this coupling method, and both single and MPP calculations were tested. MPI parallel calculation for SOLVEG2 was also applied. Moreover, this coupling method has two coupling modes: one-way and two-way coupling. In one-way coupling, only MM5 sends data to SOLVEG and no feed back from SOLVEG is considered in MM5. In two-way coupling, a dynamical link of MM5 and SOLVEG is realized by mutual data exchanges between them. Both coupling modes were examined, and the validity of this method was confirmed by reasonable model outputs. For 3-day calculation, the CPU time was 8 hours for the one-way coupling and 9 hours for two-way coupling by using 12-pe for MM5, 8-pe for SOLVEG2-domain1, and 10-pe for SOLVEG2-domain2 on Fujitsu parallel computer Primepower.

Calculated skin temperatures distribution in the domain 2 at the local noon of the third day of calculation (57 hours from the initial time) by the original MM5 calculation and SOLVEG2 calculations in offline, one-way coupling, and two-way coupling are shown in Fig. 10-4. The skin temperatures calculated by SOLVEG in the offline (Fig. 10-4b) and one-way coupling (Fig. 10-4c) were similar and mostly higher than that by the original MM5 (Fig. 10-4a). It means that SOLVEG2 calculation for assumed land surface has tendency to produce higher skin temperature than the original calculation by using the same inputs of the atmospheric variables by MM5. It is expected that the skin temperature by the two-way coupling becomes higher than that by the one-way coupling, because the higher skin temperature heats up the surface layer air, and the higher air temperature causes the further rise in skin temperature (positive feed back). However, no clear tendency of temperature rise is seen. It is considered that other meteorological fields, such as wind field, cloud, and precipitation, were also affected by the feed back so as to restrain the skin temperature rise. It indicates that this coupling realized the dynamical coupling of MM5 and SOLVEG as if SOLVEG was incorporated into MM5 like OSU-LSM.

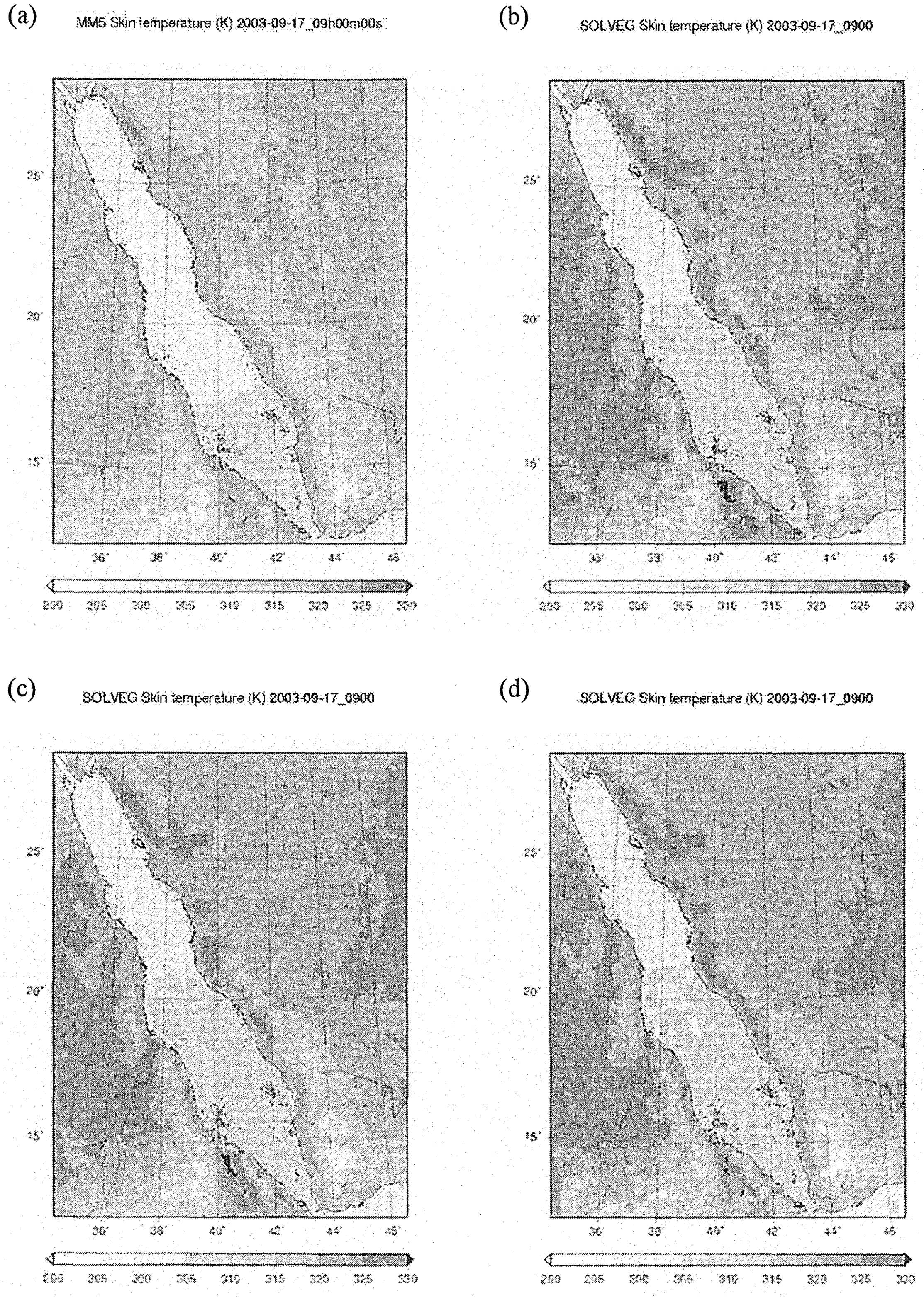

Fig. 10-4 Calculated skin temperature distribution in the domain 2 at the local noon of the third day of calculation (57 hours from the initial time) by (a) the original MM5 calculation and SOLVEG2 calculations in (b) offline, (c) one-way coupling, and (d) two-way coupling.

11. Summary

A new atmosphere-soil-vegetation model named SOLVEG2 is developed to study the heat and water exchanges at the ground surface. The model can simulate the CO_2 exchange among the atmosphere, soil, and vegetation. It also has the detailed radiation transmission scheme in the canopy. Therefore, the model can explicitly simulate all the essential exchanges (momentum, heat, water, radiation, and CO_2) at the land surface. The material transports in the atmosphere, soil, and vegetation are also studied by applying this model. For these purposes, the model is designed to simulate processes in the atmosphere-soil-vegetation system in a more realistic way than the commonly used models by using multilayer expression for the atmosphere, soil, and vegetation and avoiding uncertain parameterizations as much as possible. The present model is one-dimensional and applicable to the near-surface layer (about 10 m) of the atmosphere by using surface meteorological observations or the atmospheric model's outputs as the top boundary conditions. The model also has the function to be coupled with the atmosphere model MM5 by using the new method to couple models by MPI. In this coupling, two models are calculated independently as parallel tasks and necessary data for each model are exchanged by MPI. The model performance was examined by using measured data at the winter wheat field. The model simulated surface fluxes and other variables satisfactorily. In test calculations for coupling with MM5, reasonable model outputs proved the validity of this coupling.

In the future work, the model is planned to be coupled with land hydrology and oceanic models, and finally the coupled regional hydrological cycle model will be developed for studies of water circulation in the atmospheric, oceanic, and terrestrial environment. It is expected that this coupled model can be applied to solve problems such as desertification, drought, flood etc. It is also planned that the processes for carbon circulation in the atmosphere-soil-vegetation system are incorporated, and the model is apply for studies to understand the carbon circulation in the land surface ecosystem for the solution of global warming problem.

References

1) Yamazawa, H., and H. Nagai, 1997: Development of one-dimensional atmosphere-bare soil model (in Japanese). JAERI-Data/Code 97-041, Japan Atomic Energy Research Institute, 56 pp.
2) Nagai, H., and H. Yamazawa, 1999: Development of one-dimensional atmosphere-soil-vegetation model (in Japanese). JAERI-Data/Code 99-024, Japan Atomic Energy Research Institute, 88 pp.
3) Deardorff, J, W., 1978: Efficient prediction of ground surface temperature and moisture with inclusion of a layer of vegetation. *J. Geophys. Res.*, **83**, 1889-1903.
4) Sellers, P. J., Y. Mintz, Y. C. Sud, A. Dalcher, 1986: A Simple Biosphere model (SiB) for use within general circulation models. *J. Atmos. Sci.*, **43**, 505-531.
5) Pan, H.-L., and L. Mahrt, 1987: Interaction between soil hydrology and boundary-layer development. *Bound.-Layer Meteor.*, **38**, 185-202.
6) Noilhan, J., and S. Planton, 1989: A simple parameterization of land surface processes for meteorological models. *Mon. Wea. Rev.*, **117**, 536-549.
7) Dickinson, R. E., A. Henderson-Sellers, and P. J. Kennedy, 1993: Biosphere-Atmosphere Transfer Scheme (BATS) version 1e as coupled to the NCAR Community Climate Model. NCAR Tech. Note NCAR/TN-387+STR, 72 pp. [Available from National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307.]
8) Pleim, J. E., and A. Xiu, 1995: Development and testing of a surface flux and planetary boundary layer model for application in mesoscale models. *J. Appl. Meteor.*, **34**, 16-32.
9) Chen, F., K. Mitchell, J. Schaake, Y. Xue, H. L. Pan, V. Koren, Q. Y. Duan, M. Ek, and A. Betts, 1996: Modeling of land-surface evaporation by four schemes and comparison with FIFE observations. *J. Geophys. Res.*, **101**, 7251-7268.
10) Willson, N. R., and R. H. Shaw, 1977: A higher order closure model for canopy flow. *J. Appl. Meteor.*, **16**, 1197-1205.
11) Yamada, T., 1982: A numerical model study of turbulent airflow in and above a forest canopy. *J. Meteor. Soc. Japan*, **60**, 439-454.
12) Meyers, T. P., and K. T. Paw U, 1986: Testing of a higher-order closure model for modeling airflow within and above plant canopies. *Bound.-Layer Meteor.*, **37**, 297-311.
13) Meyers, T. P., and K. T. Paw U, 1987: Modeling the plant canopy micrometeorology with higher-order closure principles. *Agri. and Forest Meteor.*, **41**, 143-163.
14) Raupach, M. R., 1987: A lagrangian analysis of scalar transfer in vegetation canopies. *Q. J. R. Meteor. Soc.*, **113**, 107-120.
15) Shaw, R. H., and U. Schumann, 1992: Large-eddy simulation of turbulent flow above and within a forest. *Bound.-Layer Meteor.*, **61**, 47-64.
16) Nagai, H., 2002: Validation and sensitivity analysis of a new atmosphere-soil-vegetation

model, *J. Appl. Meteor.*, **41**, 160-176.

17) Nagai, H., 2003: 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, *J. Appl. Meteor.*, **42**, 434-351.

18) LeMone, M. A., R. L. Grossman, R. L. Coulter, M. L. Wesely, G. E. Klazura, G. S. Poulos, W. Blumen, J. K. Lundquist, R. H. Cuenca, S. F. Kelly, E. A. Brandes, S. P. Oncley, R. T. McMillen, and B. B. Hicks, 2000: Land-atmosphere interaction research, early results, and opportunities in the Walnut river watershed in southeast Kansas: CASES and ABLE. *Bull. Amer. Meteor. Soc.*, **81**, 757-779.

19) DePury, D. G. G., and G. D. Farquhar, 1997: Simple scaling of photosynthesis from leaves to canopies without the errors of big-leaf models. *Plant, Cell Environ.*, **20**, 537-557.

20) Bonan, G. B., 1995: Land-atmosphere CO_2 exchange simulated by a land surface process model coupled to an atmospheric general circulation model. *J. Geophys. Res.*, **100**, 2817-2831.

21) Chen, F., D. N. Yates, H. Nagai, M. A. LeMone, K. Ikeda, and R. L. Grossman, 2003: Land surface heterogeneity in the Cooperative Atmosphere Surface Exchange Study (CASES-97). Part I: Comparing modeled surface flux maps with surface-flux tower and aircraft measurements. *J. Hydrometeor.*, **4**, 196-218.

22) Yates, D. N., F. Chen, and H. Nagai, 2003: Land surface heterogeneity in the Cooperative Atmosphere Surface Exchange Study (CASES-97). Part II: Analysis of spatial heterogeneity and its scaling. *J. Hydrometeor.*, **4**, 219-234.

23) Nagai, H., 2004: Incorporation of CO_2 Exchange Processes into a Multilayer Atmosphere-Soil-Vegetation Model, *J. Appl. Meteor.*, (submitted).

24) Sellers, P. J., D. A. Randall, G. J. Collatz, J. A. Berry, C. B. Field, D. A. Dazlich, C. Zhang, G. D. Collelo, and L. Bounoua, 1996: A revised land surface parameterization (SiB2) for atmospheric GCMs. part I: Model formulation. *J. Climate*, **9**, 676-705.

25) Dickinson, R. E., M. Shaikh, R. Bryant, L. Graumlich, 1998: Interactive canopies for a climate model. *J. Climate*, **11**, 2823-2836.

26) Niyogi, D. S., and S. Raman, 1997: Comparison of four different stomatal resistance schemes using FIFE observations. *J. Appl. Meteor.*, **36**, 903-917.

27) Grell, G. A., J. Dudhia, and D. R. Stauffer, 1994: A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5), NCAR Tech. Note, NCAR/TN-398+STR, 122pp.

28) Yamada, T., 1981: A numerical simulation of nocturnal drainage flow. *J. Meteor. Soc. Japan*, **59**, 108-122.

29) Richards, L. A., 1931: Capillary conduction of liquids through porous mediums, *Physics*, **1**, 318-333.

30) Simunek, J., and D. L. Suarez, 1993: Modeling of carbon dioxide transport and production

in soil 1: Model development. *Water Resour. Res.*, **29**, 487-497.

31) Suarez, D. L., and J. Simunek, 1993: Modeling of carbon dioxide transport and production in soil 2: Parameter selection, sensitivity analysis, and comparison of model predictions to field data. *Water Resour. Res.*, **29**, 499-513.

32) Farquhar, G. D., S. von Caemmerer, and J. A. Berry, 1980: A biochemical model of photosynthetic CO_2 assimilation in leaves of C3 species. *Planta*, **149**, 78-90.

33) Collatz, G. J., J. T. Ball, C. Grivet, and J. A. Berry, 1991: Physiological and environmental regulation of stomatal conductance, photosynthesis, and transpiration: a model that includes a laminar boundary layer. *Agric. For. Meteorol.*, **54**, 107-136.

34) Collatz, G. J., M. Ribas-Carbo, and J. A. Berry, 1992: Coupled photosynthesis-stomatal conductance model for leaves of C4 plants. *Aust. J. Plant Physiol.*, **19**, 519-538.

35) Verstraete, M. M., 1987: Radiation transfer in plant canopies: Transmission of direct solar radiation and the role of leaf orientation. *J. Geophys. Res.*, **92**, 10,985-10,995.

36) Verstraete, M. M., 1988: Radiation transfer in plant canopies: Scattering of solar radiation and canopy reflectance. *J. Geophys. Res.*, **93**, 9,483-9,494.

37) Yasuda, N, 1988: Turbulent diffusivity and diurnal variations in the atmospheric boundary layer, Boundary-Layer Meteor., 43, 209-221.

38) Clapp, R., and G. Hornberger, 1978: Empirical equations for some soil hydraulic properties. *Water Resour. Res.*, **14**, 601-604.

39) Kondo, J., N. Saigusa, and T. Sato, 1990: A parameterization of evaporation from bare soil surfaces. *J. Appl. Meteor.*, **29**, 385-389.

40) Jackson, R. D., R. J. Reginato, B. A. Kimball, and F. S. Nakayama, 1974: Diurnal soil-water evaporation: Comparison of measured and calculated soil water fluxes. *Soil Sci. Soc. Am. J.*, **38**, 861-866.

41) Sander, R., 1999: Compilation of Henry's Law constants for inorganic and organic species of potential importance in environmental chemistry. (available at http://www.mpch-mainz.mpg.de/~sander/res/henry.html)

42) McCumber, M. C., 1980: A numerical simulation of the influence of heat and moisture fluxes upon mesoscale circulations. Ph.D. dissertation, University of Virginia, 255 pp.

43) Chen, F., and J. Dudhia, 2001: Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Mon. Wea. Rev.*, **129**, 569-585.

44) Cosby, B. J., G. M. Hornberger, R. B. Clapp, and T. R. Ginn, 1984: A statistical exploration of the relationships of soil moisture characteristics to the physical properties of soil. *Water Resour. Res.*, **20**, 682-690.

45) Jarvis, P. G., 1976: The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Philos. *Trans. Roy. Soc. London* B, **273**, 593-610.

46) Aphalo, P. J., and P. G. Jarvis, 1991: Do stomata respond to relative humidity? *Plant, Cell Environ.*, **14**, 127-132.

47) Mott, K., and D. Parkhurst, 1991: Stomatal responses to humidity in air and helox. *Plant, Cell Environ.*, **14**, 509-515.

48) Leuning, R, 1995: A critical appraisal of a combined stomatal-photosynthesis model for C_3 plants. *Plant, Cell Environ.*, **18**, 339-355.

49) Monteith, J., 1995: A reinterpretation of stomatal responses to humidity. *Plant, Cell Environ.*, **18**, 357-364.

50) Kim, J., and S. Verma, 1991: Modeling canopy photosynthesis: Scaling up from a leaf to canopy in a temperate grassland ecosystem. *Agric. For. Meteor.*, **57**, 187-208.

51) Jacobs, C., 1994: Direct impact of atmospheric CO_2 enrichment on regional transpiration. Ph.D. dissertation, Wageningen Agricultural University, 179pp. [Available from Wageningen Agricultural University, 6701 AP Wageningen, the Netherlands.]

52) Kondo, J., and T. Watanabe, 1992: Studies on the bulk transfer coefficients over a vegetated surface with a multilayer energy budget model. *J. Atmos. Sci.*, **49**, 2183-2199.

53) Dorman, J. L., and P. J. Sellers, 1989: A global climatology of albedo, roughness length and stomatal resistance for atmosphere general circulation models as represented by the Simple Biosphere Model (SiB). *J. Appl. Meteor.*, **28**, 833-855.

54) Weiss, A., and J. M. Norman, 1985: Partitioning solar radiation into direct and diffuse, visible and near-infrared components. *Agric. For. Meteor.*, **34**, 205-213.

55) Stephens, G. L., 1978: Radiation profiles in extended water clouds. II: Parameterization schemes. *J. Atmos. Sci.*, **35**, 2123-2132.

56) Nagai, H., 2003: New Method for Model Coupling Using Stampi: Application to the Coupling of Atmosphere Model (MM5) and Land-surface Model (SOLVEG), JAERI-Data/Code 2003-021, Japan Atomic Energy Research Institute, 36pp.

57) Imamura, T., H. Koide, and H. Takemiya, 1998: Stampi: A message passing library for distributed parallel computing – User's guide (in Japanese), JAERI-Data/Code 98-034, Japan Atomic Energy Research Institute, 29pp.

58) Yamazawa, H., 1996: Development of a numerical solution method for advection terms and its application to the atmospheric dynamic model, PHYSIC, *J. Nucl. Sci. Technol.*, **33**, 69-77.

59) Chino, M., and T. Adachi, 2003: Present status and future prospect on System for Prediction of Environmental Emergency Dose Information, SPEEDI (in Japanese), *J. Atomic Energy Soc. Japan*, **45**, 296-301.

60) Businger, J. A., W. F. Dabberdt, A. C. Delaney, T. W. Horst, C. L. Martin, S. P. Oncley, and S. R. Semmer, 1990: The NCAR Atmosphere-Surface Turbulent Exchange Research (ASTER) facility. *Bull. Amer. Meteor. Soc.*, **71**, 1006-1011.

61) Yates, D. N., F. Chen, M. A. LeMone, R. Qualls, S. P. Oncley, R. L. Grossman, and E. A.

Brandes, 2001: A cooperative atmosphere-surface exchange study (CASES) dataset for analyzing and parameterizing the effects of land surface heterogeneity on area-averaged surface heat fluxes. *J. Appl. Meteor.*, **40**, 921-937.

Appendix: Description of Model Code

Functions, include files, and variables of routines are described according to the category; main routine, primary routines, coupling routines, secondary routines, common routines, and functions.

A-1 Main Routine

SOLVEG2

Function:
- Reading and setting the input and output directory paths and CO_2 calculation switch.
- Controlling calculation flow and time step.

Include files: Inclnum, Inclcon1, Inclcon2, Inclvari, and (mpif.h*).

A-2 Primary Routines

PREAD

Function:
- Reading parameters from param_xxx.
- Reading initial data from files in the input directory or receive them from MM5.

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

Variables: None.

MSHINT(NX, NY, N2, UTY, Z, ZZD)

Function:
- Setting the atmosphere grid 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.
- 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, EMSVTYI, ALBEDOI, TURBIDI, PHPS, T0I, QS0I, CO20I, CTIME1, ZSO)

Function:
- Initializing soil and vegetation routines.
Include files: Inclnum.
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].
- 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

Function:
- Initializing atmospheric variables.
Include files: Inclnum, Inclcon1, Inclcon2, and Inclvari.
Variables: None.

FLUXCAL

Function:

- Calculating turbulent flux.

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

Variables: None.

SFPR13

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)

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

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, and Inclvari.

Variables: None.

KMHCAL

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)

Function:

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

Include files: Inclnum.

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 Soil CO_2 production distribution parameter [m^{-1}].

UMAIN(SOUV)

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)

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)

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)

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)

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}].

GRADSOUT(PATHG, CTIME1, ZSO, FSH, FLH, FGH, FLW, FNR, HWO, TSO)

Function:

- Outputting grid data as GrADS file.

Include files: Inclnum.

Variables:

- PATHG: Char*70 Grid data output directory.
- CTIME1: Char*15 Calculation time [yyyy-mm-dd_hhmm].
- ZSO(NS+1): Real*8 Soil grid depth [m].
- FSH(NX,NY): Real*8 Sensible heat flux [W m^{-2}].
- FLH(NX,NY): Real*8 Latent heat flux [W m^{-2}].
- 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].

NCOUT(PATHG, CTIME1, ZSO, DLON, DLAT, GHGT, DX, DY, X00, Y00, FSH, FLH, FGH, FLW, FNR, HWO, TSO)

Function:

- Outputting grid data as NetCDF file for the Numerical Environment System.

Include files: Inclnum and (netcdf.inc**).

Variables:

- PATHG: Char*70 Grid data output directory.
- CTIME1: Char*15 Calculation time [yyyy-mm-dd_hhmm].
- ZSO(NS+1): Real*8 Soil grid depth [m].
- DLON(NX,NY): Real*8 Longitude of model grid [deg.].
- DLAT(NX,NY): Real*8 Latitude of model grid [deg.].
- GHGT(NX,NY): Real*8 Ground elevation of model grid [m].
- DX: Real*8 X-grid interval [m].
- DY: Real*8 Y-grid interval [m].
- X00: Real*8 X-coordinate of the South-west point [m].
- Y00: Real*8 Y-coordinate of the South-west point [m].
- FSH(NX,NY): Real*8 Sensible heat flux [W m^{-2}].
- FLH(NX,NY): Real*8 Latent heat flux [W m^{-2}].
- 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].

A-3 Coupling Routines

STAMPI_START_M

Function:

- Establishing MPI connection to MM5.

Include files: (mpif.h*).

Variables: None.

STAMPI_END_M

Function:

- Confirming the calculation end with MM5.

Include files: (mpif.h*).

Variables: None.

REC_KILL_SIG_M

Function:

- Exchanging the calculation end signal with MM5.

Include files: (mpif.h*).

Variables: None.

STAMPI_MKSEND_M(FSH, FLQ, FLW, ALB)

Function:

- Making send data to MM5.

Include files: Inclnum and (mpif.h*).

Variables:

- FSH(NX,NY):	Real*8	Sensible heat flux [W m^{-2}].
- FLQ(NX,NY):	Real*8	Vapor flux [kg m^{-2} s^{-1}].
- FLW(NX,NY):	Real*8	Upward long-wave radiation flux [W m^{-2}].
- ALB(NX,NY):	Real*8	Surface albedo.

STAMPI_EXCHANGE1_M(ISTAMPI1, FLAT, FLON, GHGT, ROU, TBOTM, TWATR, STY, UTY, HWI, PHPI, RSOLI, RINFI, RRI, UI, VI, TI, QI, CO2I)

Function:

- Receiving parameters and initial data from MM5.

Include files: Inclnum and (mpif.h*).

Variables:

- ISTAMPI1:	Integer	Coupling flag [1: on, 0: off].
- FLAT(NX,NY):	Real*8	Latitude of model grid [deg.].
- FLON(NX,NY):	Real*8	Longitude of model grid [deg.].
- GHGT(NX,NY):	Real*8	Ground elevation of model grid [m].
- ROU(NX,NY):	Real*8	Air density [kg m^{-3}].
- TBOTM(NX,NY):	Real*8	Soil bottom temperature [K].
- TWATR(NX,NY):	Real*8	Sea surface temperature [K].
- STY(NX,NY):	Real*8	Soil type [1 to 16].
- UTY(NX,NY):	Real*8	Land-use type [1 to 24 USGS categories].
- HWI(NX,NY):	Real*8	Initial soil water content [m^3 m^{-3}].

- PHPI(NX,NY):	Real*8	Surface air pressure [hPa].
- RSOLI(NX,NY):	Real*8	Solar radiation flux [W m^{-2}].
- RINFI(NX,NY):	Real*8	Long-wave radiation flux [W m^{-2}].
- RRI(NX,NY):	Real*8	Rain intensity [mm h^{-1}].
- UI(NX,NY,M1):	Real*8	Wind u-component [m s^{-1}].
- VI(NX,NY,M1):	Real*8	Wind v-component [m s^{-1}].
- TI(NX,NY,M1):	Real*8	Air temperature [°C].
- QI(NX,NY,M1):	Real*8	Specific humidity [kg kg^{-1}].
- CO2I(NX,NY,M1):	Real*8	CO_2 concentration [ppmv].

STAMPI_EXCHANGE2_M(ISTAMPI1, ITIME, TIMER, PHPI, RSOLI, RINFI, RRI, UI, VI, TI, QI, CO2I)

Function:

- Sending surface boundary condition data to MM5
- Receiving top boundary condition data from MM5.

Include files: Inclnum and (mpif.h*).

Variables:

- ISTAMPI1:	Integer	Coupling flag [1: on, 0: off].
- ITIME:	Integer	Integration time [s].
- TIMER(0:1):	Real*8	Timer to control input [s].
- PHPI(NX,NY):	Real*8	Surface air pressure [hPa].
- RSOLI(NX,NY):	Real*8	Solar radiation flux [W m^{-2}].
- RINFI(NX,NY):	Real*8	Long-wave radiation flux [W m^{-2}].
- RRI(NX,NY):	Real*8	Rain intensity [mm h^{-1}].
- UI(NX,NY,M1):	Real*8	Wind u-component [m s^{-1}].
- VI(NX,NY,M1):	Real*8	Wind v-component [m s^{-1}].
- TI(NX,NY,M1):	Real*8	Air temperature [°C].
- QI(NX,NY,M1):	Real*8	Specific humidity [kg kg^{-1}].
- CO2I(NX,NY,M1):	Real*8	CO_2 concentration [ppmv].

A-4 Secondary Routines

GZSOLVEG(NX, NY, NS, NC, UTY, ZS, ZC)

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

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)

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.

GVPROFILE(NS, NC, IDATEV, ITIMEV, VTYPEI, AZI, RZI)

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].

CLSL2A

Function:

- Calculating turbulence variables by level 2.0 turbulence closure model.

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

Variables: None.

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)

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}].

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

Function:

- Calculating vapor 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].
- 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}].

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

Function:

- Calculating water 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].
- 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].

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)

Function:

- Calculating heat conduction 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].
- 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.

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)

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	Soil CO_2 production distribution parameter [m^{-1}].
- CO2S(NX,NY,0:NS):	Real*8	Soil CO_2 concentration [ppmv].
- FCO2S(NX,NY,NS):	Real*8	Soil CO2 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}].

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)

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)

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)

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}].

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)

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 [kg m^{-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}].

A-5 Common Routines

DEWTMP(QA, PHPS, TDEW)

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].

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

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.

EHWS(NX, NY, NS, TEXTURE, HWS)

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}].

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

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}].

EPPARA(NC, DZC, AZ, FA, FR)

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.

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

Function:

- Calculating heat capacity and thermal conductivity of soil.

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].
- 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}].

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

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}].

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

Function:

- Calculating diffusivity and hydraulic conductivity 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}].

- 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}].

PCAL

Function:

- Calculating air pressure profile.

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

Variables: None.

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

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}].

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

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.

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

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.

GENER(I1, J1, ID, DK, A)

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).

DIREC1(N, TOP, PE1, PF1, Q)

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.

DIREC2(N, TOP, PE1, PF1, Q)

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.

HIFI1(QN, Q, QQ0, QQ1, WI, DELT, DZ)

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].

MPGATHER4(VAR, NX, NY, NZ, IT)

Function:

- Gathering variable distributed to memories in parallel processors by MPI.

Include files: (mpif.h*).

Variables:

- VAR(NX,NY,NZ):	Real*4	Variable.
- NX:	Integer	Horizontal x-grid size.
- NY:	Integer	Horizontal y-grid size.
- NZ:	Integer	Vertical grid size.
- IT:	Integer	MPI communication tag number.

A-6 Functions

FAIM(Z, STB)

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

FAIH(Z, STB)

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

PSYM(Z, STB, ZZER)

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)

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.

SHMD(TEMP, PRESSURE, JFLG)

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}].

SHMDD(TEMP, PRESSURE, JFLG)

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}].

FCPAIR(Q)

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

FCW(T)

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

FDENSA(D, Q, T, QQ, TT)

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}].

FL(T)

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

国際単位系 (SI) と換算表

表 1　SI基本単位および補助単位

量	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
平面角	ラジアン	rad
立体角	ステラジアン	sr

表 2　SIと併用される単位

名　称	記　号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ eV = 1.60218 \times 10^{-19}\ J$

$1\ u = 1.66054 \times 10^{-27}\ kg$

表 5　SI接頭語

倍数	接頭語	記　号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

表 3　固有の名称をもつSI組立単位

量	名　称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m \cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 4　SIと共に暫定的に維持される単位

名　称	記　号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ Å = 0.1\ nm = 10^{-10}\ m$

$1\ b = 100\ fm^2 = 10^{-28}\ m^2$

$1\ bar = 0.1\ MPa = 10^5\ Pa$

$1\ Gal = 1\ cm/s^2 = 10^{-2}\ m/s^2$

$1\ Ci = 3.7 \times 10^{10}\ Bq$

$1\ R = 2.58 \times 10^{-4}\ C/kg$

$1\ rad = 1\ cGy = 10^{-2}\ Gy$

$1\ rem = 1\ cSv = 10^{-2}\ Sv$

(注)

1. 表1－5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eV および 1 u の値は CODATA の1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. bar は，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令では bar，barn および「血圧の単位」mmHg を表2のカテゴリーに入れている。

換　　算　　表

力	$N(=10^5 dyn)$	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　$1\ Pa \cdot s(N \cdot s/m^2) = 10\ P$(ポアズ)$(g/(cm \cdot s))$

動粘度　$1\ m^2/s = 10^4 St$(ストークス)(cm^2/s)

圧力	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	$J(=10^7 erg)$	kgf·m	kW·h	cal(計量法)	Btu	ft・lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J (計量法)
　= 4.184 J　(熱化学)
　= 4.1855 J　(15 °C)
　= 4.1868 J (国際蒸気表)

仕事率　1 PS (仏馬力)
　= 75 kgf·m/s
　= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

Atmosphere-soil-vegetation Model Including CO_2 Exchange Processes : SOLVEG2