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CLMT2 User's Guide: A Coupled Model for Simulation of Hydraulic Processes from Canopy to Aquifer

Version 1.0

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Abstract

CLMT2 is designed to simulate the land-surface and subsurface hydrologic response to meteorological forcing. This model combines a state-of-the-art land-surface model, the NCAR Community Land Model version 3 (CLM3), with a variably saturated groundwater model, the TOUGH2, through an internal interface that includes flux and state variables shared by the two submodels. Specifically, TOUGH2, in its simulation, uses infiltration, evaporation, and root-uptake rates, calculated by CLM3, as source/sink terms; CLM3, in its simulation, uses saturation and capillary pressure profiles, calculated by TOUGH2, as state variables. This new model, CLMT2, preserves the best aspects of both submodels: the state-of-the-art modeling capability of surface energy and hydrologic processes from CLM3 (including snow, runoff, freezing/melting, evapotranspiration, radiation, and biophysiological processes) and the more realistic physical-process-based modeling capability of subsurface hydrologic processes from TOUGH2 (including heterogeneity, three-dimensional flow, seamless combining of unsaturated and saturated zone, and water table). The preliminary simulation results show that the coupled model greatly improved the predictions of the water table, evapotranspiration, and surface temperature at a real watershed, as evaluated using 18 years of observed data. The new model is also ready to be coupled with an atmospheric simulation model, representing one of the first models that are capable to simulate hydraulic processes from top of the atmosphere to deep-ground.

1. Introduction

The land surface often becomes the boundary between different disciplines in the scientific and engineering community, because of different modeling objectives. For example, many climate models, surface-water models, and vegetation/ecology models often take the land surface as the lower boundary, parameterizing the subsurface processes in various simplified ways (e.g., runoff coefficient, evaporation coefficient). On the other hand, many physically based subsurface or groundwater models often take the land surface as the upper boundary by lumping the complex processes above the surface as known boundary conditions (e.g., net infiltration or hydraulic head). However, in nature, the hydraulic processes from canopy to aquifer often form an integrated surface-subsurface system through complicated interactions. As a result, such simplified models cannot properly describe how the real system behaves, in many cases resulting in unacceptable errors. During the last few decades, much progress has been made in development of more realistic models to simulate hydraulic interactions through the land surface. Instead of simply taking the land surface as the boundary of the modeling domain, many models simulate the lower portion of the atmosphere and upper portion of the subsurface as an integrated system, by which the atmosphere-land interactions become internal processes (Abromopoulos et al., 1988; Famiglieti and Wood, 1991; Wood et al., 1992; Liang et al., 1994; Bonan, 1998; Dai and Zheng, 1997; Walko et al., 2000; Liang et al., 2003; Olesen et al., 2004). CLM3 is one such model primarily developed to meet the needs of regional climate modeling. In CLM3, radiation, sensible and latent heat transfer, zonal and meridional surface stresses, and ecological and hydrological processes are simulated as interrelated subprocesses, using hybrid approaches (i.e., combinations of physically based dynamic modeling and experientially based parameterization models). However, the model of subsurface moisture flow in CLM3 is still overly simplified. In this regard, TOUGH2 can offer a more realistic physical process-based modeling capability for subsurface hydrologic processes (including heterogeneity, three-dimensional flow, seamless combining unsaturated and saturated zones, and water table). Coupling these two models is thus an attractive way to build a useful model of surface-subsurface hydraulic interactions.

The purposes of developing CLMT2 are (1) to improve CLM3 simulation of important atmosphere-land interaction flux, such as ET, runoff, and latent heat flux, by incorporating the sophisticated subsurface modeling capabilities of TOUGH2; (2) to extend the modeling capability of TOUGH2 to include the important energy, momentum, and moisture dynamics above the land surface provided by CLM3; and (3) to provide a sophisticated modeling tool of atmosphere-land-subsurface hydraulic interactions at watershed or regional scales, either as a stand-along model or as part of an integrated model that ranges from the atmosphere down to deep groundwater.

2. Model Description

2.1 Relationships to CLM3 and TOUGH2

The new model, CLMT2, can be seen as a combination of CLM3 and TOUGH2 (Module EOS9 only, refer to "TOUGH2" below for simplicity) in a sequentially coupling way. Therefore, it inherited most of the modeling capabilities from both CLM3 and TOUGH2. A detailed technical description of CLM3 can be found in the NCAR Technical Note (Oleson et al., 2004), whereas Wu et al. (1996) provided a summary of EOS9, an unsaturated/saturated water flow simulation module, within the TOUGH2 package.

From the perspective of CLM3, the new model no longer simulates the subsurface moisture movement as a one-dimensional process by explicit scheme. Instead, the 3-D Richards equation is solved implicitly by TOUGH2. As a result, CLMT2 can be used to simulate 1-D, 2-D, or 3-D moisture flow in a heterogeneous subsurface, including the watersheds or regions where significant human activities (e.g., pumping, irrigation, recharging) occur. In particular, the assumption that the permeability decreases exponentially from top to bottom of the soil is no longer used. Therefore, CLMT2 can be more flexible in dealing with complex subsurface environments. Table 2.1 lists the major differences in simulating subsurface flow between CLM3 and the coupled model, CLMT2.

Table 2.1 Major differences between CLM3 and CLMT2 in simulation subsurface flow

CLM3	CLMT2
Assumes that permeability decreases with depth exponentially.	The permeability is a part of user specified input parameters and can be in any spatially variable way.
Richards equation is solved explicitly (no iteration in each time step).	Richards equation is solved fully implicitly.
Clapp and Hornberger relationships are used for hydraulic functions of soil.	van Genuchten relationships are used for hydraulic functions of soil.
Hydraulic properties are assigned generally based on the soil texture classification.	Hydraulic properties are provided as input by the user for the specific site.
Soil moisture stress for root uptake is either 0 or 1 (dead or live).	A piecewise linear function is used to simulate the soil moisture stress for root uptake.
Soil columns are isolated from one another and subsurface drainage (base flow) is calculated as a value proportional to the saturation weighted average Ks in lower soil layers and exp(- WT), which is then deducted from the soil each time step.	Lateral subsurface flow if any is included naturally in three-dimensional flow simulation. No artificial subsurface drainage is included.
Soil depth is limited to 3.5 m.	Soil depth, usually larger than 3.5 meters, is specified by the user, so that the domain bottom is deeper than the water table.

From the perspective of TOUGH2, the new model no longer takes the net infiltration or root uptake as prescribed boundary conditions or source/sink terms. Instead, the net infiltration and root uptake result from simulations by CLM3 of coupled energy, wind, vegetation, and hydraulic processes. As a result, CLMT2 expands the scope of TOUGH2, such that more realistic modeling of land-surface conditions is possible.

2.2 Spatial Discretization and Grid Structure of CLMT2

The modeling domain below land surface is discretized into connected grid cells similar to a TOUGH2 grid. Different from a regular TOUGH2 grid, however, the grid cells in the upper portion (the root zone) of a CLMT2 grid must be geometrically "regular", so that they can form grid columns. The aerial extent of each grid column corresponds to the grid cell of a regional climate model. Above each grid column, nested hierarchical grid structures are created to capture land-surface heterogeneity within the area. An area can contain multiple, noninteractive "landunits" (e.g., "glacier", "wetland", "vegetated", "lake", and/or "urban"). Each "landunit" (except "lake") can contain multiple, noninteractive "snow/soil" sub-columns. Similarly, each "snow/soil" type can contain multiple, noninteractive PFTs ("plant functional type"). The term "noninteractive" indicates that there is no communication among substructures at the same level. In other words, they are logically isolated subareas splitting the entire area. Besides the "snow/soil" subcolumns, which can have multiple layers, all other substructures are one-layer or single-node structures. Note that the "soil" subcolumns spatially overlap the root zone of the subsurface grid column where the communication between TOUGH2 and CLM3 takes place. In addition, the "snow/soil" subcolumns are also used for calculations of thermal transfer and freezing/melting processes in snow cover and soil, because EOS9 of TOUGH2 does not account for those processes.

2.3 Major Processes

The major processes simulated in CLMT2 are:

- Vegetation composition, structure, and phenology
- Absorption, reflection, and transmittance of solar radiation
- Absorption and emission of longwave radiation
- Momentum, sensible heat (ground and canopy), and latent heat fluxes (ground evaporation, canopy evaporation, transpiration, dew, sublimation)
- Heat transfer in soil and snow including phase change
- Canopy hydrology (interception, throughfall, and drip)
- Snow hydrology (snow accumulation and melt, compaction, water transfer between snow layers)
- Surface hydrology (surface runoff and infiltration)
- Subsurface hydrology (vadose zone and groundwater)
- Stomatal physiology and photosynthesis
- Lake temperatures and fluxes

2.4 Governing Equations for Hydraulic Processes

Models of water flow in the subsurface are based on numerical solutions of the Richards equation:

$$\frac{\partial \theta}{\partial t} = \nabla \cdot \left[k_s k_r \nabla \psi_h\right] + q_s - q_{root} \tag{1}$$

with a flux continuation condition at land surface:

$$-k_s k_r \left.\frac{\partial(\psi_h)}{\partial z}\right|_{at\, landsurface} = q_{\inf l} \tag{2}$$

where θ, ψ_h, k_s, k_r are the volumetric water content, the hydraulic potential, the saturated hydraulic conductivity, and the relative permeability, respectively. The term q_{root} is root uptake rate while q_s indicates other source/sink terms that might exist in the subsurface (e.g., wells). The root uptake rate varies spatially and depends on the root distribution in the root zone and the transpiration from dry leaf surfaces (E_v^t):

$$q_{root} = E_v^t\, r(z) = \left[-\frac{\rho_{atm}\left(h_{can} - h_{can}^{sat}\right)}{r_b} r_{dry}\, \beta_t\right] r(z) \tag{3}$$

where $r(z)$, varying with depth z, is the effective root fraction, a product of the root fraction and the soil stress. The terms ρ_{atm}, h_{can}, h_{can}^{sat}, r_b, and β_t are the density of atmospheric air, the specific humidity of canopy air, the saturated water vapor specific humidity at the vegetation temperature, the leaf boundary stomatal resistance, and the total soil moisture stress to the root uptake, respectively. The shade factor (r_{dry}) is calculated as a function of the sunlit (L^{sun}) and shaded (L^{sha}) leaf area indices:

$$r_{dry} = \frac{f_{dry}\, r_b}{L}\left[\frac{L^{sun}}{r_b + r_s^{sun}} + \frac{L^{sha}}{r_b + r_s^{sha}}\right] \tag{4}$$

The term f_{dry} is the fraction of leaves that are dry, L^{sun} and L^{sha} are the sunlit and shaded leaf area indices, and r_s^{sun} and r_s^{sha} are the sunlit and shaded stomatal resistances, respectively.

The net infiltration rate (q_{infl}) in Equation (2) is calculated from the surface water-balance equation:

$$q_{\inf l} = q_0^{liq} - q_{runoff} - E_g \tag{5}$$

with q_0^{liq}, the rate of liquid water reaching the soil surface, which could be the summation of throughfall rate (q_{thru}^{liq}) and canopy drip rate (q_{drip}^{liq}) if no snow cover exists or the flow rate of liquid water reaching soil surface from the snow layers (including melting water). The throughfall rate is the liquid precipitation (q_{rain}) that directly falls through the canopy, and is calculated as:

$$q_{thru}^{liq} = q_{rain} \exp[-0.5(L+S)] \tag{6}$$

where L and S are the exposed leaf and stem area index, respectively. The canopy drip rate is calculated from the canopy interception model, while the flow rate of liquid water reaching the soil surface from the snow layers is an output of the snow processes model. Both models are described in detail in the NCAR Technical Note (Oleson et al., 2004) and will not be repeated here.

The other two terms in Equation (5), the surface runoff (q_{runoff}) and the water vapor flux at soil surface (E_g) along with the transpiration (E_v^t) and the net infiltration rate ($q_{\inf l}$) mentioned above are four important fluxes that connect the surface and subsurface processes in CLMT2.

If the top soil layer is not impermeable, the surface runoff is the sum of runoff from saturated and unsaturated areas:

$$q_{runoff} = \left[f_{sat} + (1 - f_{sat}) w_m^4\right] q_0^{liq} \tag{7}$$

where f_{sat} and w_m are the fraction of saturated area and the mean wetness in the top three layers, respectively. In particular, the fraction of saturated area is a function of water table depth (z_w):

$$f_{sat} = w_{fact} \min\left[1, \exp(-f_z\, z_w)\right] \tag{8}$$

where, w_{fact} and f_z are the fraction of wet land area and a constant scaling factor (f_z = 1 m^{-1}), respectively.

The water vapor flux at soil surface (E_g) reflects the net result of soil surface evaporation and dew. It is driven by the gradient of specific humidity between the ground surface and the atmosphere (nonvegetated surface) or the canopy (vegetated surface) as follows:

$$E_g = -\frac{\rho_{atm}(h_{atm} - h_g)}{r_{aw}} \tag{9a}$$

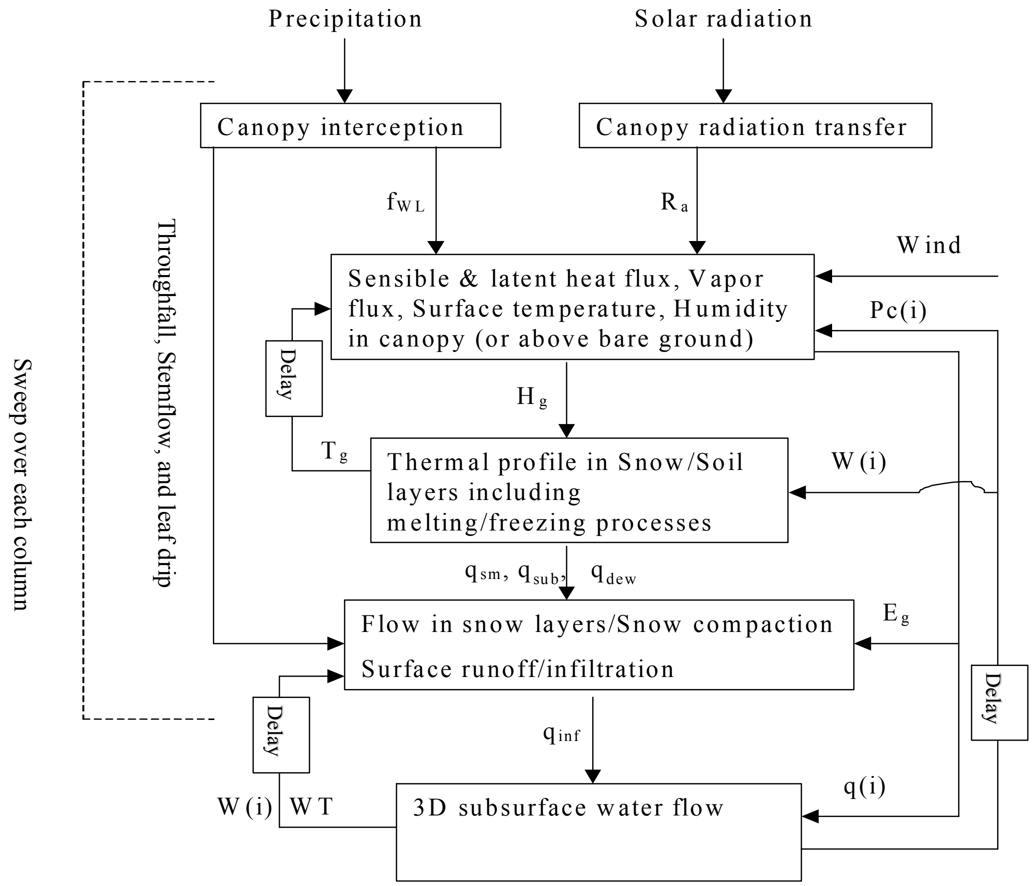
for non-vegetation surface, and

$$E_g = -\frac{\rho_{atm}\left(h_{can} - h_g\right)}{r_{agc}} \tag{9b}$$

for vegetated surface, where ρ_{atm}, h_{atm}, h_g, and h_{can} are the density of atmospheric air, the atmospheric specific humidity, the specific humidity of the soil surface, and the canopy air specific humidity, respectively. The other two terms, r_{aw} and r_{agc}, are the aerodynamic resistance to water vapor transfer between the ground and the atmospheric air at the reference height, and that between the ground and the canopy air, respectively. The aerodynamic resistances are calculated using a surface layer model, based on Monin-Obukhov similarity theory. The water vapor flux is simulated as a part of the coupled surface energy, momentum, and moisture model, described in detail in the NCAR Technical Note (Oleson et al., 2004) and not repeated here.

2.5 Numerical Implementation

Figure 2.1 shows a brief flow chart of CLMT2 for one time step. For a given meteorological forcing at each time step, CLM3 modules simulate canopy and surface processes sequentially and column by column, using the water table (WT), water content (W(i)), and capillary pressure (Pc(i)) calculated by the TOUGH2 module at the previous time step. The resulting net infiltration rate (q_{inf}) and root uptake flux (q(i)) are then used as source/sink terms in subsurface flow simulation by the TOUGH2 module.



f_{WL}— fraction of wet leaf; R_a— absorbed radiation flux; T_g,H_g— ground temperature and heat flux; q_{sm}, q_{sub}, and q_{dew} –water flux of snow melting, sublimation, and dew; E_g— evaporation at ground; q(i), W(i), and Pc(i)— root uptake flux, water content, and capillary pressure in root zone; WT— groundwater table; q_{inf}— net infiltration

Figure 2.1 Flow chart of CLMT2

Numerical solution of the subsurface water flow equation is achieved using a Newton-Raphson iteration method, based on the integrated finite difference scheme as performed in the TOUGH2 model (Wu at al., 1996). To overcome the convergence problem near the moving unsaturated/saturated interface, we use a transformed pressure as the primary variable (Pan and Wierenga, 1995).

3. Input/Output

3.1 Control File (Fixed name "control.in")

The following is an example of the control file. The left side lists the data that actually read by CLMT2, while the right side provides interpretations of the corresponding data.

"d:\clm_t2\Valdai1d\"	Path to the input data file
"scaleddrive_3HR.dat"	The file of driving force data
10800., 52592,8	dtime, nsteps, outstep
19650101	Start date of driving force data
"Valdai1D.out"	Main output
"T2input_Valdai1D.dat"	Input file needed by TOUGH2 module
"Valdai_1d_T2.out"	Output file of TOUGH2 module
"init_1d.data"	Initial file
True	Flag indicating if Lumped Weather data
2.0	Obeservation height of climate parameters (m)
True	Flag indicating if top 1 m moisture profile saved
1	Number of columns
1,36,61	ID, Nc, and the last cell ID in the column

The first row is the path where CLMT2 can find all the input files. This path is usually different from the current working directory so that the input and output files will be located in different directories. The second row is the filename of the meteorological driving force data. The first data point in the third row is the duration of one time step (in seconds) while the second and the third data on that row are the total number of time steps to be modeled and the number of time steps per one day at which the results will be saved to the main output file and other related output files, respectively. The fourth row is the date corresponding to the first record in the drive-forcing data file. The main output file, the TOUGH2 input file, the TOUGH2 output file, and the initial status file are provided from Row 5 to Row 8, respectively. If the entry on the ninth row is "True", the meteorological driving force data are the same for all columns at the same time. Otherwise, each column has its own meteorological driving force for each time step. Similarly, if the entry on the eleventh row is "True", the saturation profile in the top 1 m of soil will be saved to "soilSat.dat". Otherwise, it will not be saved. The value in the tenth row indicates the height (m) at which the air temperature and humidity are observed. The observation height of wind speeds is fixed at 10 m in CLMT2. The number in Row 12 is the number of columns within the modeling domain, followed by this number of rows of data. Each such row contains three numbers: the grid cell ID, the number of cells that serves as the internal interfaces between CLM3 and TOUGH2 modules, and the last cell ID in that column (the bottom cell). The grid cells in a TOUGH2 mesh are ordered column by column from top to bottom. Therefore, the cell ID is the naturally ordered number of each cell. Note that these parameters actually define the root zone where the CLM3 module and TOUGH2 module are coupled. Therefore, special caution must be put toward developing the numerical grid for TOUGH2 module and toward specifying these parameters, to keep a consistent root zone between the two modules. The last row contains the first baseflow connection ID and number of such connections in the TOUGH2 mesh. Here, the term baseflow connections refers to the connections related to the inactive cells (i.e., cells with constant pressure), by which the interaction between the stream and the groundwater can be approximated.

3.2 The File of Meteorological Forcing Data

Each row contains, in order, one set of drive forcing data, including total incident solar radiation (W/m^2) , downward longwave radiation onto surface (W/m^2), total precipitation (mm/s), air temperature (Kelvin), zonal wind (m/s), meridional wind (m/s) , air pressure (Pa), and air specific humidity (kg/kg). For the lumped weather case (the entry in the ninth row of the control file above is true), the number of rows in this file shall be equal to or larger than the total number of time steps. In the case in which the columns have different meteorological drive force data, this number shall be at least the product of the number of time steps and the number of columns.

3.3 TOUGH2 Input File

The input data and formats are the same as those for the TOUGH2 EOS9 module (Wu et al., 1996), except that the hydraulic function type in the “ROCKS” card has to be 7 (i.e., van Genuchten function). In addition, all “root zone” cells (i.e., the cells that will be used for interactions between CLM3 and TOUGH2 modules) must have the same thickness as those used in CLM3 module. The “COM1” type source/sink terms must also be assigned to these “root zone” cells in the required “GENER” card, ordered column by column (from top down in each column). If there are any other source/sink terms (e.g., wells), they have to be placed behind those “root zone” source/sink terms in the “GENER” card.

3.4 Initial File

Each row of data defines the surface parameters and the initial conditions for one column. They includes longitude of the column (degrees), latitude of the column (degrees), land type index (1 = land; 0 = ocean), vegetation type index, soil type index, the upper ceasing potential (mm H2O), the lower ceasing potential (mm H2O), land-surface elevation (m), fraction of wet land that covers the column, snow depth (mm H2O), air temperature (Kelvin), temperature at soil surface (Kelvin), and temperature at bottom of root zone (Kelvin). Here, the upper ceasing potential is the soil moisture potential above which the root uptake will cease, whereas the lower ceasing potential is the soil moisture potential below which the root uptake will cease.

USGS 24 categories of vegetation are used for a vegetation type index, as follows:

Vegetation Type	Index
Urban and Built-Up Land	1
Dryland Cropland and Pasture	2
Irrigated Cropland and Pasture	3
Mixed Dryland/Irrg. C.P.	4
Cropland/Grassland Mosaic	5
Cropland/Woodland Mosaic	6
Grassland	7
Shrubland	8
Mixed Shrubland/Grassland	9
Savanna	10
Deciduous Broadleaf Forest	11
Deciduous Needleleaf Forest	12
Evergreen Broadleaf Forest	13
Evergreen Needleleaf Forest	14
Mixed Forest	15
Water Bodies	16
Herbaceous Wetland	17
Wooded Wetland	18
Barren or Sparsely Vegetated	19
Herbaceous Tundra	20
Wooded Tundra	21
Mixed Tundra	22
Bare Ground Tundra	23
Snow or Ice	24

The soil type index entered here is primarily used to define the thermal parameters of soils. Soil hydraulic properties are defined in the TOUGH2 input file. The following 19 categories of soil type are used for soil type index:

Soil Type	**Index**
Sand	1
loamy-sand	2
sandy-loam	3
silt-loam	4
Silt	5
Loam	6
sandy-clay-loam	7
Silty-clay-loam	8
clay-loam	9
sandy-clay	10
Silty-clay	11
Clay	12
Organic-material,	13
Water	14
Bedrock	15
other(land-ice)	16
Playa	17
Lava	18
White-sand	19

3.5 Main Output File

This file contains output data for each column at each time step. They are time (days), precipitation (mm/s), surface runoff (mm/s), ET (mm/s), net infiltration (mm/s), latent heat flux (W/m^2), land surface temperature (Kelvin), snow depth (mm H2O), groundwater depth (m), thickness of frozen soil (m), and soil moisture (mm) above 20 cm, 50 cm, and 100 cm depth, respectively.

3.6 TOUGH2 Output File

The formats are the same as those for the TOUGH2 EOS9 module (Wu et al., 1996). The output data will depend on the specifications defined in the TOUGH2 input file.

3.7 Mean Discharge and ET File (Fixed name "TotalDischargeET.dat")

This output file contains the mean discharge rate (surface runoff + baseflow) and mean ET of the entire domain (including all columns) at each time step. Specifically, each row of data includes time (days), mean discharge rate (mm/s), and mean ET (mm/s).

3.8 Soil Saturation Profile (Fixed name "soilSat.dat")

This output file contains the saturation of the top 1 m of soil for each column at each time step. Each row of data includes time (years), depth (m, negative value), and saturation (m^3 /m^3).

3.9 Input and Output for Coupling with Atmospheric Model

CLMT2 can be easily coupled to MM5 (an atmospheric model). In this case, instead of taking meteorological drive-forcing data from a disk file as described before, CLMT2 can take the same set of atmospheric input as CLM3 (see Table 1.1, Olesen et al., 2004) and provide the same output to the atmospheric model (Table 1.2, Olesen et al., 2004).

4. Examples

Usadievsky Watershed, Valdai, Russia, is a midlatitude grassland catchment, with deep snow cover in the winter and significant precipitation in the summer. Eighteen years observation data gathered from this site were used extensively within the Project for Intercomparison of Land-surface Parameterization Scheme (PILPS) and provided a very robust validation for surface-subsurface models (Maxwell and Miller, 2005). The hydraulic parameters used in this study are the same as those in Maxwell and Miller (2005). The entire catchment (0.36 km^2) is simulated as a 1-D column down to the depth of 6 m, which is below the minimum water table in the site. All of the observations were made available by Robock et al. (2000) and Luo et al. (2003) as part of the Global Soil Moisture Databank. The precipitation data within the original meteorological forcing data were scaled in 3 hr interval by the observed monthly precipitation, so that the precipitation as model input was consistent with the observed ones at temporal scale of month.

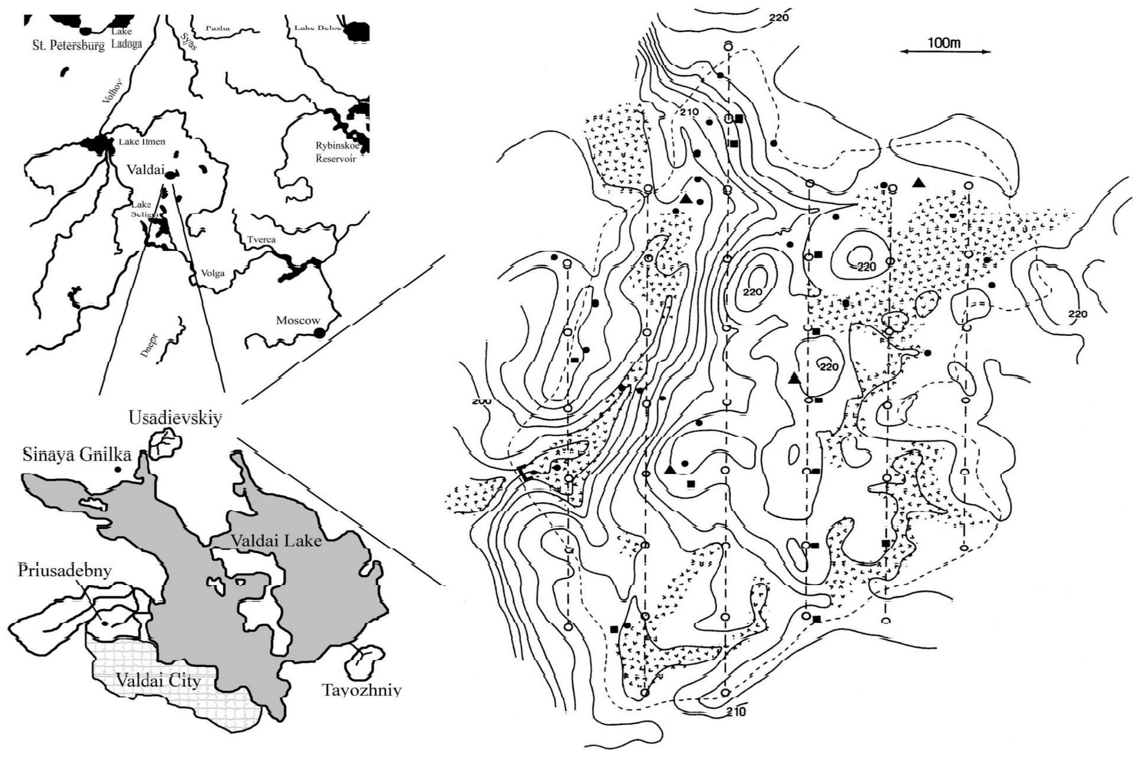


Figure 4.1. Map of the Usadievskiy catchment at Valdai, Russia and its location (Courtesy of Luo et al., 2003) . Filled circles are water-table measurement sites. Open circles with dashed lines indicated the snow measurement sites and routes, respectively. Discharge is measured at the stream outflow point of the catchment (see bold bracket) at the lower left-hand corner of the catchment map. Filled triangles indicate the measurement sites of soil freezing and thawing depths.

Table 4.1 Model parameters used in Vaidai simulation

Parameter	Value	Unit
van Genuchten alpha	1.95	m^{-1}
van Genuchten exponent	1.74	
Saturated hydraulic conductivity	1.21	m/day
Effective soil porosity	0.401	m^3/m^3
Residual saturation	0.136	
Lower critical point at which root uptake stops	-5270.81	mm H2O
Upper critical point at which root uptake stops	0.1	mm H2O
Fraction of model area with high WT	0.15	
Latitude	57.6N	Degree
Longitude	33.1E	Degree
Vegetation type index	7 (grassland)	
Soil type index	6 (loam)	

Simulated daily snow depths are presented in Figure 4.1. Both CLM3 and CLMT2 predict almost identical results that agree well with the measured snow depth (the dots). This convergence between the two models is expected because of the halt in surface-subsurface hydraulic interactions during the frozen winter season. As a result, the accuracy of the subsurface simulation does not matter in simulating the snow accumulation processes on the land surface.

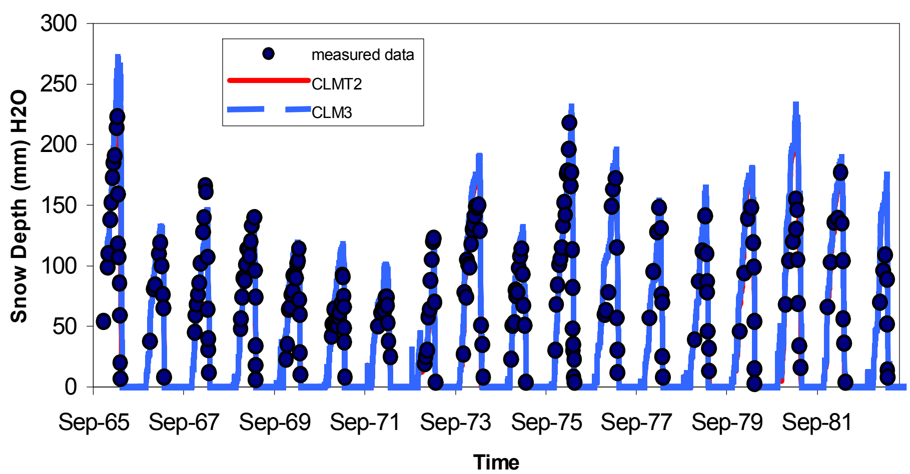


Figure 4.1. Simulated and observed snow depth

However, CLMT2 does significantly improve the predictions of monthly evapotranspiration (ET) (Figure 4.2). As shown in Figure 4.2, CLM3 underestimated the ET compared with the measured data, while CLMT2 agrees well with the measure data. Consistent with the underestimating of ET, CLM3 often overestimates the surface temperature during the summer season (Figure 4.3). Obviously, the coupled model, CLMT2, is more accurate in this case as well. These results indicate that the impact of subsurface flow on surface processes during nonfrozen seasons is significant, and that correctly simulating the subsurface flow is very important.

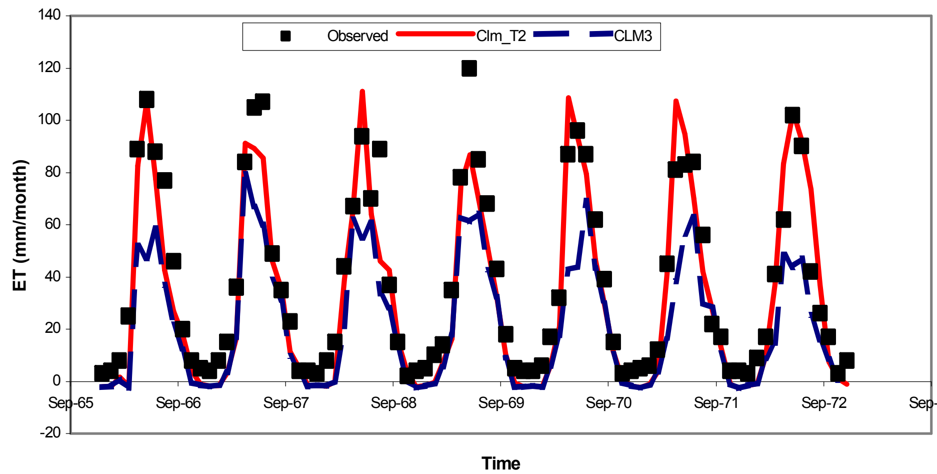


Figure 4.2. Simulated and observed monthly ET

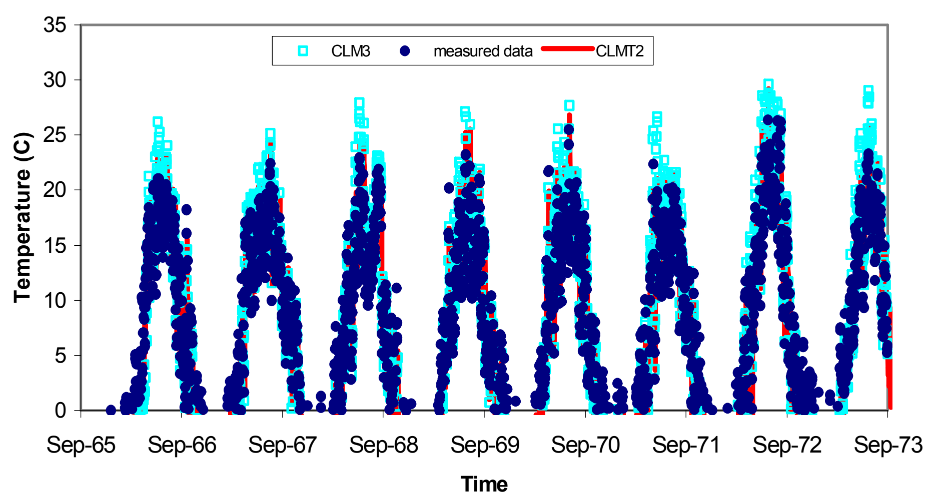


Figure 4.3. Simulated and observed ground surface temperature

Figure 4.4 compares the observed daily water tables (WT) with those simulated by CLM3 (blue line) and CLMT2 (red line), respectively. The observed WT data are a site average of 19 observation wells at a subweek scale. CLM3 uses a special parameterization scheme to calculate the WT from the wetness of the soil profile, whereas the WT is automatically determined as the interface between the unsaturated and saturated soil layers simulated by CLMT2. As shown in Figure 4.4, CLMT2 replicated most groundwater seasonal responses to the meteorological forcing. CLM3, however, poorly estimated such responses, especially in magnitude of WT variations.

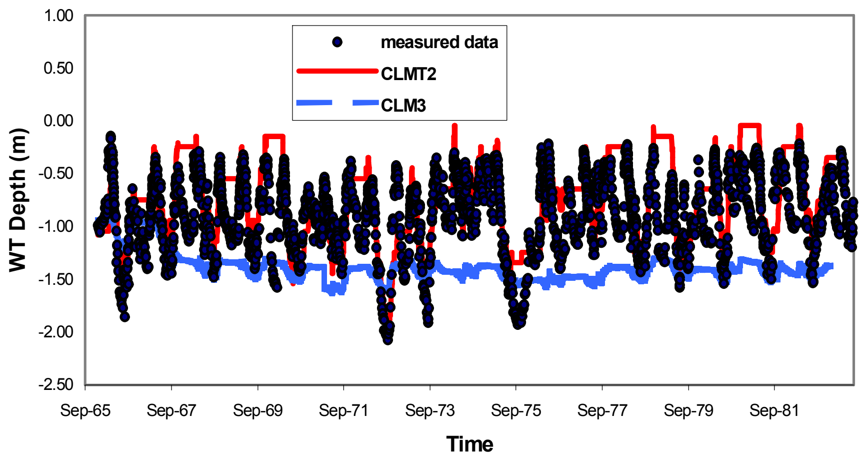


Figure 4.4. Simulated and observed daily water table (WT)

5. Concluding Remarks

CLMT2, a model that combines the ability to simulate the land-surface and subsurface hydrologic responses with meteorological forcing, has been developed. This new model was created by combining a state-of-the-art land surface model, the NCAR Community Land Model version 3 (CLM3), with a variably saturated groundwater model, TOUGH2, through an internal interface that includes flux and state variables shared by the two submodels. This new model preserves the best aspects of both submodels: the state-of-the-art modeling capability of surface energy and hydrologic processes from CLM3 (including snow, runoff, freezing/melting, evapotranspiration, radiation, and biophysiological processes) and the more realistic physical-process-based modeling capability of subsurface hydrologic processes from TOUGH2 (including heterogeneity, three-dimensional flow, seamless combining of unsaturated and saturated zone, and water table).

Eighteen years of observed data from Usadievsky Watershed, Valdai, Russia, was used to evaluate the performance of the coupled model. Compared to CLM3, the new model, CLMT2, greatly improved the predictions of the water table, evapotranspiration, and surface temperature at the real watershed. This is particularly true in nonfrozen seasons when the interactions between surface and subsurface are significant. These results also indicate that correct simulation of subsurface flow (including the water table) is very important in simulation of surface processes such as evapotranspiration or land surface temperature, the two most important feedback factors for regional climate.

The new model is also ready to be coupled with an atmospheric simulation model, representing one of the first models that are capable to simulate hydraulic processes from top of the atmosphere to deep-ground.

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Appendix List of Source Code Files

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accFldsMod.F90
accumulMod.F90
BalanceCheckMod.F90
BareGroundFluxesMod.F90
biochem_to_mm5.F90
Biogeophysics1Mod.F90
Biogeophysics2Mod.F90
BiogeophysicsLakeMod.F90
biophy_to_mm5.F90
Calendr.f90
CanopyFluxesMod.F90
Clm_init.f90
clm_varcon.F90
clm_varpar.F90
clm_varsur.F90
Clm3.f90
CLM3FCMod.F90
Clmi.f90
CLM-T2_mod.for
Clmtype.f90
clmtypeInitMod.F90
CLMZEN.F90
CommonData.f
d1ma_pc.for
dblas1.f
decompMod.F90
DGVMAllocationMod.F90
DGVMEcosystemDynMod.F90
DGVMEstablishmentMod.F90
DGVMFireMod.F90
DGVMKillMod.F90
DGVMLightMod.F90
DGVMMod.F90
DGVMMortalityMod.F90
DGVMReproductionMod.F90
DGVMTurnoverMod.F90
DRIVER.F90
DriverInitMod.F90
ENDRUN.F90
Eos9_k.f
EOS9p.f
filterMod.F90
FracWetMod.F90
FrictionVelocityMod.F90
GLOBALS.F90
HYdroFunc.f
Hydrology1Mod.F90
Hydrology2Mod.F90
HydrologyLakeMod.F90
initGridCellsMod.F90
InitialConditions.f
initializeMod.F90
iniTimeConst.F90
```

```
iniTimeVar.F90
inter9.for
MKRANK.F90
nanMod.F90
pcapecm.for
pft2colMod.F90
pftvarcon.F90
PREPROC.H
QSatMod.F90
relpecmn.for
rootresistant.for
shr_kind_mod.F90
sndsaf.for
SnowHydrologyMod.F90
SoilHydrologyMod.F90
SoilTemperatureMod.F90
STATICEcosysDynMod.F90
subgridAveMod.F90
SurfaceAlbedoMod.F90
SurfaceRadiationMod.F90
surfFileMod.F90
t2cgs1.for
t2f_s1.for
tough2.prm
TridiagonalMod.F90
UpdateSS.f
VOCEmissionMod.F90
watsit1.for
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