Chapter 45
Land Surface Improvements

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Abstract Land surface processes play an important role in the climate system. In this chapter, some improvements to parameterizations of land surface processes are introduced, including representation of water table dynamics, inclusion of anthropogenic groundwater exploitation, development of a frozen soil model considering the freezing–thawing interface, representation of crop growth, and development of a land surface model. Furthermore, the development of our land data assimilation system will be also described in this chapter.

Keywords Land surface processes · Groundwater · Frozen soil · Crop growth and development · Land data assimilation

45.1 Introduction

Land surface processes are essential to facilitate water and energy exchange between the land surface and the atmosphere. In particular, groundwater and vegetation dynamics have considerable impacts on land–atmosphere interactions at both the local and regional scales through their effects on precipitation interception and soil moisture via transpiration and evaporation and on the partitioning of net radiation into latent and sensible heat fluxes. Macroscale variations of shallow groundwater can result in variations in the horizontal and vertical distributions of soil moisture, which are responsible for adjustments in the land–surface heat and moisture fluxes and influence precipitation through convection and/or advection (Yuan et al. 2008). Meanwhile, as a specific type of vegetation, agriculture crops are characterized by their wide distribution, short growth cycle, large

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seasonal change, and vulnerability to human activities. Consequently, their growth and development processes play a critical role in defining local, regional, and global climates (Chen and Xie 2011). Therefore, investigation of the effects of groundwater dynamics and crop growth and improvements in the understanding of hydrological and ecological characteristics (and of the environment as a whole) are of great significance for weather and climate. Conversely, although current state-of-the-art land surface models can capture much of the spatiotemporal variability of soil moisture, model results typically contain mean biases and may deviate from the true soil moisture evolution owing to uncertainties in model parameters, structures, and input forcing data (Tian et al. 2008a). Land data assimilation involves the combination of complementary information from measurements and models of the land surface into a superior estimate of geophysical fields of interest and is becoming increasingly important in land surface improvement (Tian et al. 2009, 2010a).

45.2 Representation of Water Table Dynamics

The representation of water table dynamics in land surface and atmospheric models has provided important sights into water fluxes at the interface between the land surface and the atmosphere. Liang et al. (2003) reduced groundwater modeling to a moving boundary problem for the Variable Infiltration Capacity (VIC) model. Yang and Xie (2003) further reduced the moving boundary problem to a fixed boundary problem through a coordinate transformation. Many previous studies have demonstrated the need for groundwater representation in land surface schemes because of the sensitivity of soil moisture and runoff to water table depth (Yeh and Eltahir 2005a, b; Niu and Yang 2007; Miguez-Macho et al. 2007). Studies investigating the coupling of groundwater with the atmosphere have demonstrated the potential advantages of such coupling (Anyah et al. 2008). Similarly, our previous research (e.g., Yuan et al. 2008) incorporated the groundwater model developed by Yang and Xie (2003) into the RegCM3 regional climate model (Pal et al. 2007) to investigate the potential effects of water table dynamics on simulation of soil moisture profiles and study land surface fluxes and the overlying large-scale atmospheric process.

The groundwater model used in our research is based on the parameterization derived by Liang et al. (2003). Assuming $\alpha(t)$ is the groundwater table depth (L), which represents the distance from the ground surface to the water table, the following coordinate transform can be conducted (Yang and Xie 2003): $x = \dfrac{z}{\alpha(t)}$, $\tau = t$. Then, the groundwater model can then be described as a fixed boundary problem, as follows:

$$\begin{cases} \dfrac{\partial\theta}{\partial\tau} - \dfrac{x}{\alpha}\dfrac{d\alpha}{d\tau}\dfrac{\partial\theta}{\partial x} = \dfrac{\partial}{\partial x}\left(\dfrac{D(\theta)}{\alpha^2}\dfrac{\partial\theta}{\partial x} - \dfrac{K(\theta)}{\alpha}\right) - S(z,\,\tau), \\[2mm] \left[K(\theta) - \dfrac{D(\theta)}{\alpha}\dfrac{\partial\theta}{\partial x}\right]\bigg|_{x=0} = q_0(\tau), \\[2mm] \theta(x,\,\tau)|_{x=1} = \theta_s, \\[1mm] \theta(x,\,0) = \theta_0(x), \quad \text{for } 0 \leq x \leq 1, \\[1mm] \left[K(\theta) - \dfrac{D(\theta)}{\alpha}\dfrac{\partial\theta}{\partial x}\right]\bigg|_{x=1} = Q_b(\tau) + E_2(\tau) - \eta_e(\tau)\dfrac{d\alpha}{d\tau}, \end{cases} \tag{45.1}$$

where θ is the volumetric soil moisture content (L^3/L^3), $D(\theta)$ is the hydraulic diffusivity (L^2/T), $K(\theta)$ is the hydraulic conductivity (L/T), S($z,\,\tau$) is the sink item, $q_0(\tau)$ is the flux across the surface (i.e., $z = 0$), θ_s is the soil porosity (L^3/L^3), $Q_b(\tau)$ is the base flow (L/T), $E_2(\tau)$ is the transpiration from the root region in the saturated zone (L/T), and $n_e(\tau)$ is the effective porosity of the porous media (L/L).

By integrating the transformed Richards equation over (0, 1), Eq. (45.1) can be solved numerically by the finite element method as described in Liang et al. (2003).

Therefore, the water table dynamics problem can be solved numerically by iteratively applying a finite element method in space and a finite difference method in time. Yuan et al. (2008) coupled a groundwater model with BATS (BATS_GW), which is the land surface component of RegCM3; in the coupled model RegCM3_GW, soil moisture is calculated using the dynamic water table as the lower boundary. Comparison of the simulations produced by RegCM3_GW and RegCM3 suggests that dynamic representation of the water table in a regional climate model changes the surface heat and moisture fluxes by modifying the vertical distribution of soil moisture and that these differences in simulated surface fluxes result in different boundary layers, ultimately affecting convection. The cooling effects of increased evapotranspiration (ET) on the low-level atmosphere and the heating effects of the latent heat released by condensation on the upper atmosphere contribute to changes in the wind field via the thermal wind relation. Moreover, local water table-induced variations in water vapor can affect the surrounding areas through advection, indicating that the feedback between groundwater and the atmosphere cannot be explained by local land–atmosphere interactions alone. Therefore, it is essential to analyze macroscale atmospheric processes in more detail.

Recently, a quasi-three-dimensional variably saturated groundwater flow model (Xie et al. 2012) was also developed with the intention of providing a dynamic representation of lateral groundwater flow and discharge to streams. In particular, it is hoped that implementation of this model may help link groundwater, river, or lake reservoirs with a coupled land surface scheme.

45.3 Anthropogenic Groundwater Exploitation

Owing to its high quality, groundwater has been exploited widely to meet human demand for water, particularly in regions with a pronounced lack of surface water. However, excessive exploitation of groundwater reduces groundwater storage, decreases stream flow, and weakens hydraulic interaction between aquifers and rivers.

To evaluate the effects of groundwater exploitation and consumption on climate, a groundwater scheme was incorporated into a regional climate model. The Haihe River basin, where groundwater is overexploited, was chosen as the study area.

First, a scheme representing anthropogenic groundwater exploitation and consumption was adopted in the regional climate model RegCM4. In this scheme, Exploiting water from the stream flow and groundwater meet certain human water demand D_t for each time step (Fig. 45.1). The volumes of exploited river water and groundwater in the model are represented by Q_s and Q_g, respectively. The total exploited water resources can be used in three ways: agricultural irrigation D_a, industrial consumption D_i, and domestic consumption D_d. The irrigation water consumption reaches the topsoil directly as effective rainfall; conversely, industrial and domestic water consumptions are assumed to be consumed through evaporation and wastewater discharge into stream channels (W_r).
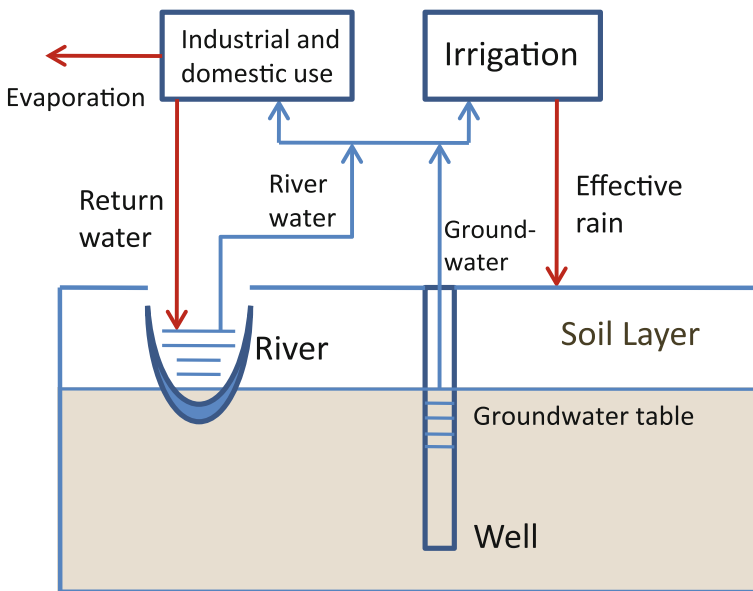
Fig. 45.1 Framework of water resource exploitation and consumption processes (adapted from Zou et al. 2013a, b)

Fig. 45.2 Sketch
of interactions between the
atmosphere and the land
surface (adapted from
Zou et al. 2013a)
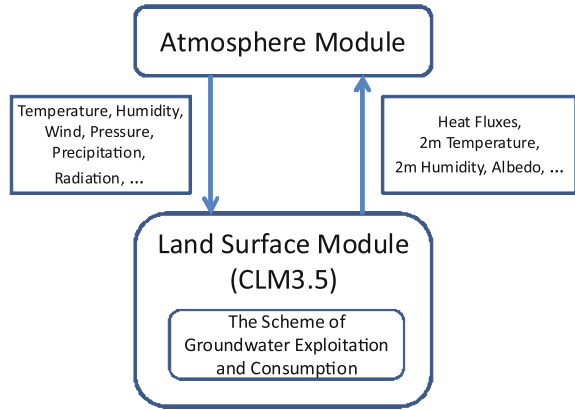
The scheme is then coupled into the land surface model CLM3.5. The volume of water exploited from rivers Q_s is considered to be subtracted from the total water quantity in rivers. The volume of water exploited from groundwater Q_g is inserted into the water storage calculation in CLM3.5 and can be expressed as follows:

$$W_{n+1} = W_n + \left(q_{recharge} - q_{drain} - Q_g\right)\Delta t, \qquad (45.2)$$

where W_{n+1} and W_n are water storage for time steps $n+1$ and n, respectively, and Δt is the interval between time steps.

The effective rain in the land model is increased by D_a owing to irrigation in the water consumption process. Wastewater recharge into rivers due to industrial and domestic consumption (W_r) is represented by $\alpha(D_i + D_d)$; this parameter is considered to flow into rivers and cannot be reused. The remaining amount of water used for industrial and domestic consumption is assumed to increase the evaporation by $(1-\alpha) \times (D_i + D_d)$.

Based on this newly developed scheme, other variables in land surface processes will change subsequently in response to changes in water storage, evaporation, and effective rainfall (Fig. 45.2). The changes in the atmosphere induced by interactions between the land surface and the atmosphere will further influence the land surface via changes in air temperature, precipitation, and humidity, among others.

The Haihe River basin, which lies in northern China, was chosen as the study area owing to the severe overexploitation of its groundwater resources. Two online simulation runs (Test 1, Test 2) with different water demands and a control run (CTL) without exploitation were designed to detect impacts on regional climate and the sensitivities of the climatic responses to different water demands. Three offline tests were also constructed to detect the roles of direct changes and indirect climatic feedback in the basin. Based on the simulation results we conclude the following. (1) Groundwater exploitation and consumption in the Haihe River basin cause rapid decreases in local land water storage, amplifying wetting and cooling

effects on the local land surface and in lower troposphere. (2) Reallocation of land water resources can also affect climate change in the regions surrounding the basin. (3) Changes in the land surface variables in Test 2 (which involves lower water demand) are much less pronounced than those in Test 1 (which involves higher water demand). (4) Without considering changes in climatic forcing, the direct changes in land surface variables found in both exploitation tests exhibit almost linear relationships with water demand.

45.4 Frozen Soil Model with Freezing–Thawing Interface Considered

A soil heat and water transfer model that incorporates the dynamic variability of soil freezing and thawing fronts has also been developed (Wang et al. 2013a). In this model, seasonal changes in the positions of the freezing and thawing interface within the active layer has been reduced to a moving boundary problem. An adaptive mesh method that includes the frost and thaw interface as mesh points for the moving boundary problem was also adopted to solve the relevant equations. The proposed model explicitly tracks the variation and dynamics of the active layer by computing the moving interface/boundary between the frozen zone and the unfrozen zone. Therefore, the proposed heat and water transfer model describes simultaneously the liquid water and solid ice states as well as the position of the freezing/thawing fronts in soil.

The developed model was coupled to the Community Land Model CLM (version 3.5). Soil temperature was calculated using freezing and thawing fronts as mesh points; then, soil liquid and ice content were adjusted by the phase change. Of particular note is that the land surface model with dynamic representation of the position of the freezing and thawing interface was able to simulate changes in the freezing and thawing fronts, thus improving the ability of the model to simulate soil moisture and temperature.

45.5 Representation of Crop Growth and Development

The CERES phenological growth and development functions were incorporated into RegCM3 to represent interactions between crop growth processes and regional climate over the East Asian monsoon area.

Crop Estimation through Resource and Environment Synthesis version 3.0 (CERES v3.0; Jones and Kiniry 1986) is a process-oriented dynamic crop growth model that predicts the status of crops on a real-time basis. In the present study, the wheat, maize, and rice models of CERES were adopted, because these are the primary crops grown in China. To represent the crop growth and development

processes in RegCM3, the CERES model was synchronously coupled to BATS (Chen and Xie 2011, 2012). CERES receives weather variables (including minimum temperature, maximum temperature, and radiation), surface variables (including surface albedo), and soil variables (including soil moisture) from BATS and simulates crop growth and development processes in a daily time step. BATS uses CERES outputs such as leaf area index, stem area index, and root fraction as inputs; then, BATS uses this daily updated data to simulate surface fluxes with a time step of 180s. The coupled regional climate model was named RegCM3_CERES.

Numerical experiments demonstrated that the coupled model can capture not only the responses of crop growth and development processes to parameters such as incoming solar radiation, soil moisture, and temperature, but also the feedbacks between crop growth and development processes and land surface processes. Comparison of the CSM and CTL runs demonstrated that decreases in leaf area index and fractional vegetation cover decreased canopy interception, vegetation transpiration, total evapotranspiration, and topsoil moisture, but increased soil evaporation, surface runoff, and root zone soil moisture.

Comparison of simulations by RegCM3_CERES and RegCM3 demonstrated that the robust representation of crop growth and development in a regional climate model can modify vegetation characteristics, resulting in differences in simulated surface fluxes. In particular, changes in leaf area index and fractional vegetation cover affected the distribution of evapotranspiration and heat fluxes and, consequently, influenced the overlying atmospheric circulation. These changes redistributed water and energy through advection, implying that the parameterizations for crop growth resulted in higher temperatures and lower evapotranspiration and precipitation values than those found for the control run over the extratropical Northern Hemisphere summer.

45.6 Development of Land Data Assimilation

Considerable effort has been made to improve knowledge of soil moisture variability through estimation of soil moisture fields using land surface models forced with realistic precipitation and other atmospheric data. Such data include the Global SoilWetness Project (http://grads.iges.org/gswp/; Dirmeyer et al. 1999), the North America Land Data Assimilation System (NLDAS; Mitchell et al. 2004), the Global Land Data Assimilation System (GLDAS; http://ldas.gsfc.nasa.gov/), and others (e.g., Nijssen et al. 2001; Qian et al. 2006; Sheffield and Wood 2008). However, because these efforts currently do not assimilate observational soil moisture data, they are not data assimilation systems in the conventional sense.

Tian et al. (2008a) and Tian and Xie (2008) developed a land surface soil moisture data assimilation system based on the dual EnKF method and the NCAR Community Land Model (version 2.0). Experiments for two sites in northern and southern China demonstrated that this dual UKF-based assimilation system can

outperform typical UKF- and EKF-based methods in reproducing the temporal evolution of daily soil moisture, particularly under freezing conditions. Furthermore, these improvements also propagated, albeit to a lesser extent, to lower layers for which observations were unavailable.

Subsequently, considerable effort has been devoted to the development of POD-based ensemble four-dimensional variational method (referred to as PODEn4DVar; Tian et al. 2008b, 2011) by coupling 4DVar with EnKF (e.g., Lorenc 2003; Tian et al. 2008b; Zhang et al. 2009a; Cheng et al. 2010; Jia et al. 2013). This method aims to fully exploit the strengths of the two forms of data assimilation while simultaneously offsetting their respective weaknesses. The method was proposed based on the Monte Carlo concept and the proper orthogonal decomposition (POD) technique. The feasibility and effectiveness of the modified PODEn4DVar were demonstrated using a two-dimensional shallow-water equation model with simulated observations. It was found that PODEn4DVar performs robustly and is capable of outperforming the local ensemble transform Kalman filter (referred to as LETKF), its 4D extension 4D-LETKF, and another ensemble-based 4DVar method under both perfect and imperfect model scenarios (Tian and Xie 2012).

Recently, to make use of satellite microwave observations in the estimation of soil moisture, Tian et al. (2010a) developed a dual-pass microwave land data assimilation system (referred to as DLDAS) by incorporating the dual-pass assimilation framework (Tian et al. 2009) into the Community Land Model version 3 (CLM3). Simultaneously, several key parameters in the radiative transfer model (RTM) were also optimized using the ensemble proper orthogonal decomposition-based parameter calibration approach (EnPOD_P; Tian et al. 2010b) in the parameter optimization pass to account for their high variability or uncertainty.

45.7 Summary

In our study, a groundwater dynamics model has been developed continuously to help improve representation of dynamic interactions between the surface and groundwater in land surface modeling. We further coupled this groundwater dynamics model, an anthropogenic groundwater exploitation scheme, and a crop growth and development model (CERES v3.0) into RegCM. These three representations of land surface processes changed surface heat and moisture fluxes by modifying vegetation characteristics, the vertical profile of soil moisture, and the available quantity of water that reaches the surface in intake areas, respectively. The differences in simulated surface fluxes resulted in different structures of the boundary layer and ultimately affected the convection.

Compared with the control run, the coupled models alleviated systematic errors in precipitation and 2 m mean temperature simulations over East Asia, at least to some extent. Variations in leaf area index and fractional vegetation cover caused changes in the distribution of evapotranspiration and heat fluxes, which led to anomalies in geopotential height and, consequently, influenced the overlying

atmospheric circulation. It should be noted that the response of precipitation to LAI was highly nonlinear. The feedback between groundwater and the atmosphere should also be explained by local land–air interactions and macro scale atmospheric processes. The cooling effect of increased evapotranspiration on the low-level atmosphere and the heating effect of the latent heat released by condensation on the upper atmosphere were found to contribute to changes in the wind field via the thermal wind relation, and local water table-induced variations in water vapor were found to affect the surrounding areas through advection. These improvements in the simulation of land surface processes could be incorporated into the land surface component of the FGOALS climate system model in future.

Additionally, a land data assimilation system has been developed by incorporating a dual-pass assimilation framework into the Community Land Model version 3 (CLM3). The entire assimilation process can be divided into two passes: one for pure assimilation, and another for parameter calibration. In the assimilation pass, the entire soil moisture profile is assimilated according to the PODEn4DVar method by utilizing brightness temperature measurements. Several key parameters can also be calibrated in the calibration pass according to the EnPOD_P method, which also uses the brightness temperature observations for the same time step.