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EXCERPT OF DISSERTATION

Water and Heat Transfer Mechanics in the Soil-Plant-Atmosphere Continuum and Regional Evapotranspiration Model *

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Abstract Three models were constructed for estimating water and heat transfer in the Soil-Plant-Atmosphere Continuum (SPAC) in different spatial and temporal scales. Three kinds of experiments have been conducted for the models at two Agro-ecosystem Stations, Chinese Academy of Sciences in the North China Plain, since 1998. The first model is the Coupled canopy Photosynthesis-Conductance-Evapotranspiration (ET) Model (CPCEM), which was applied to simulate CO_2 and water fluxes above plant canopies well, compared with the measurement. The second one is the one-dimension and three-layer Soil Water Balance (SWB) model, which was successfully used to simulate soil water deep percolation and ET under different irrigation schedules in 1998—2003. The third one is the regional energy fluxes and daily ET model, which is based on remotely sensed and synchronous surface data. It was successfully used to estimate surface energy fluxes and daily ET in a regional scale.

Key words soil-plant-atmosphere continuum (SPAC), water and heat transfer mechanics, evapotranspiration (ET) model

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Estimation of water and heat transfer in the Soil-Plant-Atmosphere Continuum (SPAC) is very important for studying soil water balance, water transfer in plants, water and CO_2 interaction between plants and atmosphere, water and energy balance in the farmland, eddy transfer in the atmospheric bound layer, and irrigation planning, etc. Several international projects are being focused on the water and energy fluxes, which include the Biospheric Aspects of the Hydrological Cycle (BAHC) core project of the International Geosphere-Biosphere Programme (IGBP) and the Global Energy and Water Cycle Experiment (GEWEX) program by the World Climate Research Programme (WCRP). Several hot topics of these projects are being focused on modeling water and energy fluxes in different ecosystems, experiments in different spatial and temporal scales, and scaling schemes on fluxes from field to regional scale and from regional to global scale.

In this study, we analyzed the water, energy and CO_2 fluxes, and soil water balance based on the long-term field experiments. Then, we constructed three independent models, including a Coupled canopy Photosynthesis-

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Conductance-Evapotranspiration Model (CPCEM) , a one-dimension and three-layer Soil Water Balance (SWB) model , and a regional energy fluxes and daily evapotranspiration (ET) model. The experiments are conducted at two Agro-ecosystem stations in the North China Plain (NCP) . One is Luancheng Agro-ecosystem Station , the other is Yucheng Compostive Station , both belongs to Chinese Academy of Sciences. Totally , three experiments were designed for the three models , respectively. The experiments include the experiment of water and energy fluxes in the SPAC , the experiment of SWB in different irrigation schedules , and the synchronous surface evapotranspiration experiment with satellite data from LANDSAT-5 and LANDSAT-7.

In the first experiment , two kinds of methods , the Bowen Ratio Energy Balance (BREB) technique and the eddy covariance technique , measured latent , heat and CO_2 fluxes above crop canopies in 1998—2003 , respectively[1] . In the second one , a neutral probe was measured soil water content in a 20 cm step in 0—200 cm soil layers under different irrigation schedules , 1998—2003[2,3] . In the third one , we synchronously measured surface temperature , surface albedo , vegetation index , and other relative variables , e. g. air temperature , wind speed , and vapor pressure deficit on the satellite overpass time , 2001.

The CPCEM , based on the water and energy fluxes experiment , was established to simulate water , energy and CO_2 fluxes in the SPAC. The model is composed of a two-layer evapotranspiration submodel based on the Shuttleworth-Wallance method , a two-source multi-layer radiation submodel , a multi-layer photosynthesis submodel which distinguishes shade and sunlit leaves , and a coupled photosynthesis-canopy conductance submodel.

The SWB model , based on the SWB experiment , was established to simulate the seasonal variation of soil water content in the three soil layers , soil water percolation (including capillary rise) . The model consists of a two-layer evapotranspiration submodel based on the dual crop coefficient method and a soil water movement submodel. The soil layers from 0—200 cm in the model were divided into three layers : the surface layer , which is mainly controlled by soil evaporation , the middle layer , which is controlled by the crop transpiration , and the deepest layer , which is controlled by soil water percolation or capillary rise.

The regional energy fluxes and daily evapotranspiration model , based on remotely sensed and synchronously surface data , was established to estimate regional surface moisture , regional latent heat flux and regional daily evaporation. There are two methods in the model applied to estimating the surface moisture which is called surface Temperature-Vegetation Cover Index (TVCI) , "Universal triangle" method and "Actual triangle" method. "Universal triangle" method is referenced according to Carlson , *et al*. ; "Actual triangle" method is estimated TVCI according to the trapezoid correlation between surface temperature and fractional vegetation cover. Daily evapotranspiration in the model is estimated according to an improved sine curve[4] .

Principal Results

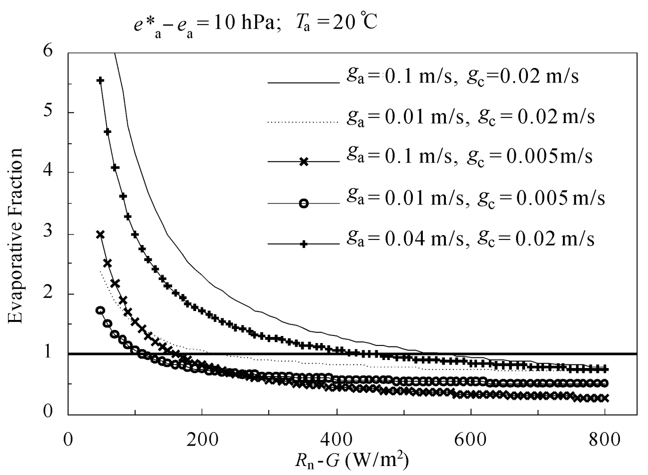
As told above , large numbers of experimental data were acquired for the three models. And , the data successfully evaluated the models. There are many valuable results based on the experimental data and the model simulation. Here , we only draw out some important results as follows.

(1) Different methods measured plant canopy water and energy fluxes. The results show that the eddy covariance is a steady method. Whereas , the measurement with the eddy covariance was easily low even if it can accurately measure sensible and CO_2 flux , which causes non-energy balance above the plant canopy. BREB technique estimated latent heat flux well , compared with the measurement of a Large-scale weighing lysimeter. The main problem of the method is that it is evidently influenced by advection[1,5] .

(2) Seasonal variation of the energy fluxes shows that latent heat flux is a main component of the energy fluxes in the NCP. Over 70 % of net radiation was evapotranspirated from wheat and maize canopy in 1999—2000 , which

showed that water on the land surface of the NCP was mainly exported by evapotranspiration[6,7].

(3) Seasonal variation of evaporation fraction (EF) was accorded with that of leaf area index (LAI), which proves that LAI is one of the most important factors controlling the evaporation fraction on a seasonal scale. Influencing opening of the stomata, soil moisture impacts latent heat transfer and water losses in the SPAC. And, evaporation fraction is changed with the soil moisture. A theoretic analysis between soil moisture and stomata shows stomatal conductance is gradually reduced to zero with the decrease of soil moisture below a soil moisture threshold[8]. Evaporative fraction can be expressed as a function of plant status and atmospheric boundary layer conditions (Fig. 1). The relationship between EF and available energy under moderate air temperature and vapor pressure deficit conditions was examined for five combinations of aerodynamic and canopy conductance. Although the theoretical relationship indicates that EF should be highly correlated to soil water content, the correlation has been difficult to identify under field conditions. However, we observed that there exists a threshold value of available energy, above which EF is less than 1.0, and that the threshold value is lower under soil-water deficit conditions than under abundant soil-water conditions.



All curves represent moderate air temperature (T_a = 20 ℃) and vapor pressure deficit (e_a^* - e_a = 10 hPa) conditions.

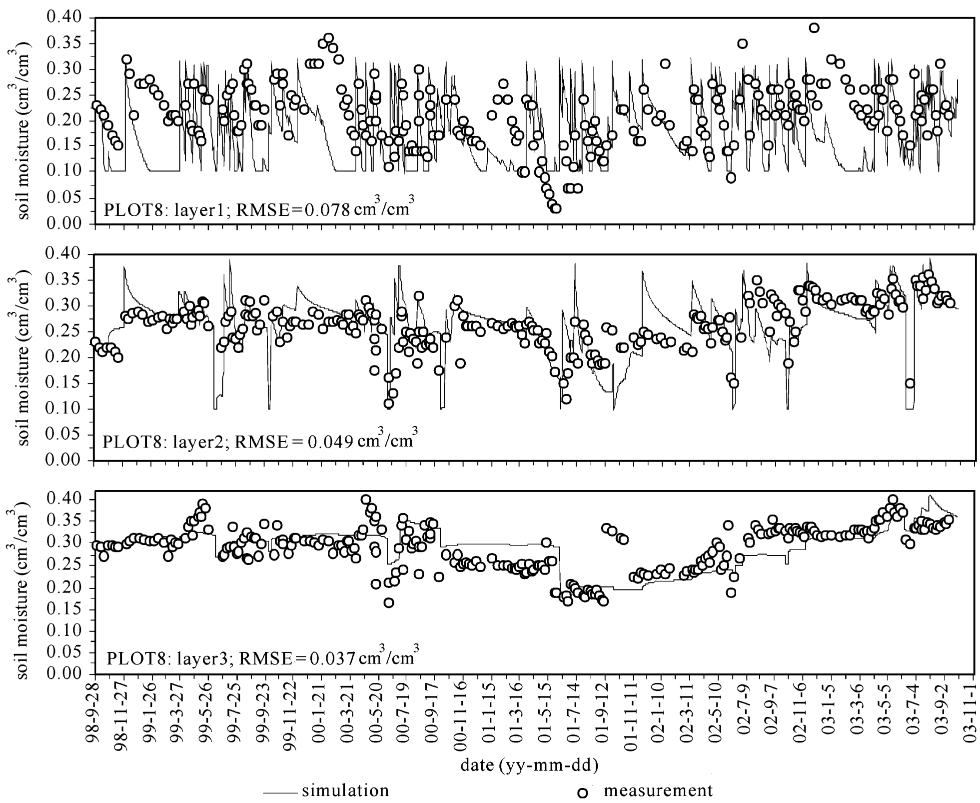
Fig. 1 Relationship between evaporative fraction (EF) and available energy (R_n-G) under a range of aerodynamic (g_a) and canopy conductance (g_c) values

(4) Solar radiation is one of most important meteorological factors affecting plant photosynthesis and evapotranspiration through influencing stomatal conductance. On the field scale, a rectangular hyperbola was successfully applied to simulate canopy photosynthesis rate which is depending on solar radiation. Strong solar radiation can inhibit crop photosynthesis rate and reduce crop water use efficiency (WUE) not only on a leaf scale, but also on a field scale[2].

(5) The CO_2 flux with the CPCEM was correlated well to that by the eddy covariance system. Whereas, latent heat flux with the CPCEM was slightly higher than that by the eddy covariance even if the seasonal trend of latent heat flux with the two methods is similar. The ratio of soil evaporation (λE_s) to total evapotranspiration (λE) with the CPCEM showed a similar seasonal pattern to that with the measurement. And, canopy conductance with the CPCEM was compared well with that by the Penman-Monteith method. Canopy WUE with the CPCEM was higher than that by the measurement owing to lower λE by the eddy covariance. Canopy photosynthesis rate is sensitive to the nitrogen content coefficient of plant leaves because it determines the maximum photosynthesis rate in different canopy layers. Also, the empirical curative factor (α) and leaf inclination angle (χ) evidently influence the photosynthesis rate. Soil evaporation in the CPCEM is sensitive to the attenuation coefficients of wind speed and net radiation. Whereas, these coefficients impact little on the total canopy evapotranspiration.

(6) There appeared a similar seasonal variation and a good correlation between the evapotranspiration in the SWB model and that by the Large-scale weighing lysimeter. Seasonal variation of soil moisture in the three soil layers with the CPCEM followed well with that by the measurement under different irrigation schedules (Fig. 2.). Soil moisture in the top soil layer was simulated well except for the overwintering stage because the SWB model neglected the impact of snow cover in the winter season; soil moisture in the middle layer was simulated best, compared with the measured; soil moisture in the lowest layer was underestimated under soil water deficit conditions

instead of normal irrigation condition. The underestimation was probably caused by the underestimation of the capillary water rise or by the erroneous simulation of root depths under soil water deficit conditions. In the SWB model, growth of root depths for winter wheat and maize was referenced the results under normal irrigation condition. The SWB model totally simulated evapotranspiration , soil water movement , and soil water percolation , etc. , 1998 —2003. According to the simulation , several conclusions were drawn as follows : ①inputted water by irrigation and precipitation is mainly evaptranspirated by soil and crops[9] ; ②evident soil water deep percolation was produced under normal irrigation schedules on the farmland of the North China Plain ; ③in soil water deficit conditions , soil water deep percolation and capillary water rise both act on the lowest soil layer. And , capillary water rise can exceed the soil water percolation under severe soil water deficit conditions.



PLOT8 is an experimental plot (5 ×10 m^2) ; Layer 1 , Layer 2 and Layer 3 are three layers in the estimated soil depth (0 —200 cm) ; RMSE represents the root mean square error.

Fig. 2　Seasonal variation of soil water content (cm^3/cm^3) at three dynamic soil layers : soil evaporation layer , crop transpiration layer , and soil water percolation layer , between the simulation with the SWB model and the measurement with a neutral-probe

(7) “Universal triangle ”and “Actual triangle ”methods in the regional energy fluxes and daily ET model are applied to estimate regional surface moisture and latent heat flux. Latent heat flux , based on the “Actual triangle ” method , compared well with that by the BREB technique , while it based on the “Universal triangle ”method is underestimated , compared with the BREB technique[10]. Similarly , daily ET based on the “Actual triangle ” methods was compared well with that by the Large-scale weighing lysimeter , while daily ET based on the “Universal triangle ”methods was underestimated. Thus , “Actual triangle ” method is better than the “Universal triangle ” method in the North China Plain even if the method was applied under different climate conditions. Variation of minimum stomatal conductance evidently impacts the latent heat flux. In our study , it was given as a number-50 s/

m according to our measurements. Surface variables, vegetation height, wet bulb temperature, vapor pressure deficit, total solar radiation and wind speed can evidently impact the latent heat flux. Thus, the precise estimation of latent heat flux and sensible heat flux must depend on the remotely sensed data and synchronous surface experiment. The "actual triangle" method can estimate the surface Temperature-Vegetation Cover Index (TVCI) and monitor surface dryness situation well in a regional scale, which can provide a theoretic base for monitoring drought in a large regional scale.

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土壤-植被-大气系统水和热传输机理及区域蒸散模型

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摘　要　在不同空间和时间尺度上建立了估算土壤-植被-大气系统水、热传输的模型, 并且在华北平原中国科学院两个农业生态试验站设计了 3 个试验, 验证模型的精度和有效性. 第一个模型是基于瞬时通量观测基础上建立的植被冠层光合-导度-蒸散耦合模型, 它模拟的结果与涡度相关系统测定结果比较一致; 第二个模型为一维 3 层的土壤水量平衡模型, 此模型成功用于模拟 1998—2003 年度太行山山前平原不同灌溉条件下的土壤水分深层入渗和蒸散过程; 第三个模型为区域能量通量和日蒸散模型, 它基于卫星遥感数据和地面同步观测而建立, 本模型可以监测区域地表的干旱状况, 用于估算区域能量通量和日蒸散.

关键词　土壤-植被-大气系统, 水热传输机理, 蒸散模型

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