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Modeling the spatial–temporal dynamics of water use efficiency in Yangtze River Basin using IBIS model

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ABSTRACT

Climate change alters regional water and carbon cycling, which has been a hot study point in the filed of climatology and ecology. As a traditionally "water-rich" region of China, Yangtze River Basin plays an important role in regional economic development and ecosystem productivity. However, the mechanism of the influence of climate change on water and carbon cycling has been received little attention. As a coupling indicator for carbon and water, the water use efficiency (WUE) is widely used, which indicates the water consumption for carbon sequestration in watershed and regional scale. A lot of studies showed that climate change has significantly affected the water resource and production of the ecosystems in Yangtze River Basin during the period of 1956–2006, when great climate variations were occurred. To better understand the alternation pattern for the relationship between water and carbon cycling under climate change at regional scale, the WUE and the spatiotemporal variations patterns were simulated in the study area from 1956 to 2006 by using the Integrated Biosphere Simulator (IBIS). The results showed that the WUE spatial pattern had the annual and seasonal variations. In general, the average annual WUE value per square meter was about 0.58 g C/kg H_2O in Yangtze River Basin. The high WUE levels were mainly distributed in the eastern area of Sichuan, western area of Jiangxi and Hunan, and the highest value reached 0.88 g C/kg H_2O. The lowest WUE's were mainly located in the western area of Sichuan and Qinghai with the lowest values reaching to 0.36 g C/kg H_2O. The WUE in other regions mostly ranged from 0.5 to 0.6 g C/kg H_2O. For the whole study area, the annual WUE slowly increased from 1956 to 2006. The WUE in the upper reaches of Yangtze River increased based on the simulated temporal trends, which mainly located in the western area of the Sichuan Basin; the WUE of the middle reaches of Yangtze River had increased slightly from 1987 to 1996, and then decreased from 1996 to 2006; the lower reaches of Yangtze River always had smaller WUE's than the average from 1956 to 2006. The spatiotemporal variability of the WUE in the vegetation types was obvious in the Yangtze River Basin, and it was depended on the climate and soil conditions, and as well the disturbance in its distribution areas. The temporal variations of WUE among different vegetation types had similar trends but different in values. The forest type had higher WUE than any other vegetation types ranging from 0.65 to 0.8 g C/kg H_2O. The WUE of shrubland ranged from 0.45 to 0.6 g C/kg H_2O. The WUE of tundra was the lowest, indicating the differences in plant physiology. The consistence of the spatial pattern of WUE with the NPP indicated that the regional production of Yangtze River Basin increased based on the water resources prompted and vegetation restoration. We found the drought climate was one of critical factor that impacts the alteration of WUE in Yangtze River Basin in the simulation.

1. Introduction

The increased atmospheric CO_2 concentration and nitrogen deposition and more-intense droughts have affected the carbon

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and water cycles in terrestrial ecosystems [1]. In fact, the carbon and water interaction effect is strongly coupled under climate change [2]. Water use efficiency (WUE), as an important indicator of carbon and water coupling, is used to quantify the trade-off of carbon assimilation and water loss. It links the carbon cycle and the hydrological cycle.

WUE has been a study hot spot in plant ecology, agriculture, and earth system science [3–6]. At different scale levels, WUE has different meanings because of the different complexity of physical and physiological processes involved. At leaf level, how to improve productivity efficiently [7–9] has been addressed. Some studies focused on the responses of WUE to environmental factors in semi-arid plant physiology, based on the traditional measurements of vegetation biomass and soil hydrological parameters [10,11]. These approaches have an obvious limitation since the continuous temporal and spatial results are unavailable [12]. Some new methods such as eddy covariance technique were developed for studying ecosystem carbon and water exchange at multiple timescales [13]. Although these new approaches brought more improvements for studying WUE at ecosystem level, it was still difficult to get a regional and continual level results of WUE which could represent a larger scope than eddy covariance techniques (approximately 1 ha) [14]. Meanwhile, as a powerfully tools to extrapolate current and future information, ecosystem process-based model had the advantages to estimate spatial–temporal WUE continually at multiple scales. Especially at regional scale, terrestrial biosphere model has its advantages to evaluate the responses of WUE to climate change [15].

As a source of industrial power and irrigation for agriculture, Yangtze River is the longest river in China, including China's numerous plant types and ecosystems [16]. Under more extensive climate change and anthropogenic activities, the ecosystems in Yangtze River Basin will therefore undertake more complex environmental pressure. To better understand the influence of climate change on the water and carbon cycles of terrestrial ecosystems, it is important to evaluate the WUE in the Yangtze River Basin of China.

In this study, a terrestrial ecosystem model called Integrated Biosphere Simulator (IBIS) has been used to simulate the carbon and water processes and calculate the spatial–temporal variations of WUE in Yangtze River Basin from 1956 to 2006. Spatial and statistical analysis methods are applied to analyze the characteristics of WUE in different plant functional types.

2. Material and methods

2.1. Study area

The study area includes the Yangtze River and its tributaries, ranging from E90°30′ to E122°25′, N24°30′ to N35°45′. The river runs 1,800,000 km from the glacier on the Tibetan Plateau eastwards across southwest, central and eastern China. Its average annual precipitation and evapotranspiration is 1067 mm and 541 mm, respectively. Because of the complexity of its climate and topographical conditions, the spatial pattern of annual precipitation and evapotranspiration is highly heterogeneous. Vegetation covers are mainly warm-temperate broadleaf evergreen forest, temperate conifer evergreen forest, and Tibet Plateau grassland.

2.2. Model description

IBIS was designed to integrate a variety of terrestrial ecosystem process within a physically consistent framework. It included multiple components that represent land surface processes, canopy physiology, vegetation phenology and carbon cycling [17]. The model was proved to be well simulating the land surface processes at different scales [18,19].

IBIS was based on a combination of plant functional types, which were defined from several important ecological characteristics [20]. A modified version of IBIS was developed to improve the original model in some aspects such as nitrogen deposition module [21], sub-pixel processing that considered vegetation and non-vegetation fractionation on each land pixel was also included.

The land surface module in IBIS was constructed on the basis of the land-surface-transfer scheme (LSX) [22,23], which presented two canopy layers, three snow layers, and six soil layers. The total evapotranspiration in each grid unit was calculated from the sum of three water vapor flutes: evaporation from soil surface, evaporation from vegetation canopy surface, and canopy transpiration. The rates of evapotranspiration velocity depended on the canopy conductance. The calculation equations were described as follows:

$$E_u = \rho s_u \left[f_u^{\mathrm{wet}} + \frac{(1 - f_u^{\mathrm{wet}}) f_u^{\mathrm{sto}}}{1 + r_u s_u} \right] (q_{\mathrm{sat}}(T_u) - q_{12})$$

$$E_s = \rho S_s f_s^{\mathrm{wet}} (q_{\mathrm{sat}}(T_s) - q_{12})$$

$$E_l = \rho s_l \left[f_l^{\mathrm{wet}} + \frac{(1 - f_l^{\mathrm{wet}}) f_l^{\mathrm{sto}}}{1 + r_l s_l} \left(\frac{\mathrm{LAI}_l}{\mathrm{LAI}_l + \mathrm{SAI}_l} \right) \right] (q_{\mathrm{sat}}(T_l) - q_{34})$$

where the subscripts 'u', 's', and 'l' denote upper-story leaves, upper-story stems, lower-story vegetation, E_u, E_s, and E_l were fluxes of water vapor from a unit leaf/stem surface area including evaporation of intercepted water, dew formation and transpiration, LAI_l and LAI_u represented the upper and lower canopy index respectively.

The algorithm of soil evaporation was using beta method [24]:

$$E_g = \rho C_E U_a \beta (q_s - q_a)$$

where E_g was the evaporation from bare soil, ρ was the air density, C_E was the drag coefficient for evaporation, U_a was the wind speed at Z_a (atmospheric reference level), β was the moisture availability parameter, q_a was the specific humidity at Z_a, q_s was the saturated specific humidity which is given by surface temperature.

The canopy physiology module included photosynthesis and stomatal conductance, which were based on a canopy photosynthesis mechanism model and a semi-mechanistic model of stomatal conductance [25,26]. The NPP calculation differed from each other in different plant functional types:

$$\mathrm{NPP} = (1 - \eta) \int (A_g - R_a) dt$$

where A_g was gross canopy photosynthesis, R_a was the rate of gross plant respiration.

For C_3 plants:

$$A_g \approx \min(J_E, J_C)$$

where J_E was the light limited rate of photosynthesis, J_c was the Rubisco limited rate of photosynthesis.

For C_4 plants:

$$A_g = \min(J_1, J_E, J_C)$$

where $J_E = \alpha_4 Q_p$, α_4 was the intrinsic quantum efficiency for CO_2 uptake in C_4 plant (mol CO_2 Ein^{-1}), $J_C = V_m$, and $J_1 = kC_i$ was the CO_2 limited rate of photosynthesis at low-CO_2 concentrations. The detailed descriptions were available in Foley et al. and Kucharik et al. [20,27].