HYDROLOGICAL EVALUATION AND IMPROVEMENT OF A DYNAMICAL GLOBAL VEGETATION MODEL AT THE BASIN SCALE

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Vegetation and the water cycle are intrinsically coupled. However, the description of interactions and feedbacks between them is insufficient in stand-alone hydrological models. Dynamic global vegetation models (DGVMs), which are able to simulate transient structural changes in major vegetation types, are well-suited tools for evaluating interplay between them. Here, the hydrological performance of Lund-Postdam-Jena model (LPJ), a prominent DGVM, is evaluated. Modification is made to runoff generation of LPJ since it is less reliable for runoff production. Simulations have been made over 98 years for four basins located in the Asian Pacific region ranging from humid to arid zones. The runoff calculated by the modified LPJ agrees well with observations. Modeled vegetation in terms of leaf area index (LAI) were validated against remotely sensed data. Additionally, to evaluate effects of vegetation on runoff and show the potential advantages of LPJ over stand alone hydrological models, as an example, the model was run under a scenario of changing atmospheric CO_2 content alone and the results show that runoff increased in humid basins while decreased in arid basins.

Keywords: *Vegetation, runoff, dynamic global vegetation models, CO_2 effect, basin scale*

1. INTRODUCTION

Vegetation plays a pivotal role in the hydrological cycle. The composition and distribution of vegetation are of fundamental importance for evapotranspiration and runoff generation. Plants exert considerable effects on runoff via features such as albedo and interception, stomatal behaviour and transpiration, rooting strategy, leaf area and phenology[1)]. In turn, water availability is a key determinant for the distribution and productivity of vegetation. Therefore, there is a need to model dynamic interactions and feedbacks between the vegetation and the water cycle.

Some researchers have tried to consider vegetation effects on hydrological processes in terms of runoff and evapotranspiration by using hydrological models. Examples include those of Tague *et al.*[2)], Oudin *et al.*[3)], and Donohue *et al.*[4)]. These researches have a detailed description of hydrological processes such as runoff and routing while an insufficient parameterization of vegetation composition and distribution. Therefore, important biosphere—hydrosphere interactions may not be well considered by such stand-alone hydrological models. For example, they cannot sufficiently capture hydrological effects resulting from changes in vegetation. Therefore, realistic assessment of vegetation change effect on hydrological processes needs models that mechanistically link vegetation dynamics and hydrological process. Among candidate models to meet this requirement are land surface schemes used in climate models, but they also do not simulate transient changes in vegetation structure and distribution[1)]. Alternative candidates are dynamic global vegetation models (DGVMs), which are able to simulate transient structural changes in major vegetation types in response to variations in climate, water availability, and atmospheric CO_2 content. Few researches[1),5),6)] have been done about evaluating the hydrological performance of DGVMs and these researches focus on annual/monthly runoff and evapotranspiration calculation at global, regional, and large river basins.

Under the changing climate conditions, understanding the vegetation dynamics and effects of vegetation on runoff at a daily step for basin scale is important for practical flood controlling and water management. However, few researches have discussed this topic.

The present study evaluates hydrological performance of a leading DGVM, the Lund-Potsdam-Jena model[6] (hereafter LPJ). The scope is to evaluate the hydrological performance of LPJ, identify limitations in runoff simulation by LPJ and improve its performance, and explore potential advantages of LPJ over stand-alone hydrological models. Therefore, simulations have been made for the period 1901-1998 for four basins located in the Asian Pacific region ranging from humid to arid zones where 9-year hydrological observation data is available for validation. Additionally, vegetation type and composition produced by the DGVM were validated against remotely sensed data. To provide an idea to what extent vegetation affects runoff at basin scale and show the potential advantages of DGVM over stand-alone hydrological models, as an example, the model was run under a scenario of changing atmospheric CO_2 content alone.

2. METHODOLOGY

(1)The Lund-Potsdam-Jena model

Lund-Potsdam-Jena (LPJ) is a coupled non-equilibrium biogeography-biogeochemistry model, which combines process-based representations of terrestrial vegetation dynamics and land-atmosphere carbon and water exchanges in a modular framework. For a detailed description of the model see Sitch *et al.*[6]. LPJ explicitly considers key ecosystem processes such as vegetation growth, mortality, carbon allocation, and resource competition, although their representation is of intermediate complexity to allow for global applications. To account for the variety of structure and functioning among plants, 10 plant functional types (PFTs) are distinguished. The presence and fractional coverage of PFTs is determined annually according to individual bioclimatic, physiological, morphological, and fire-resistance features. The structure and distribution of the PFTs is decisive for the simulated site water balance, since evapotranspiration, soil water content, and runoff generation are modulated by PFT-specific attributes such as interception storage capacity, seasonal phenology, rooting depth, and photosynthetic activity. A brief introduction of water balance computations in LPJ is given in the following sections.

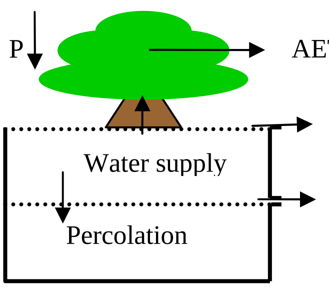

Fig.1 Schematic representation of the water balance component in LPJ.

a) Actual evapotranspiration

The actual evapotranspiration (AET) is calculated at a daily time step as the minimum of a supply function (S) and a non-water-stressed evapotranspiration rate (D)[7]:

$$AET = \min\{S, D\} \quad (1)$$

D is calculated as a function of potential canopy conductance (gp) following Monteith[8]:

$$D = E_q \alpha_m \left[1 - \exp\left(-g_p / g_m\right)\right] \quad (2)$$

where E_q is the daily total equilibrium evaportanspiration calculated from latitude, temperature and sunshine hours data. g_p is calculated according to photosynthesis, which is calculated as a function of LAI, temperature, atmospheric CO_2 concentration, day length, and canopy conductance. The parameters α_m and g_m are empirical parameters with $\alpha_m = 1.4$ and $g_m = 5$ following Monteith[8]. D gives the evapotranspiration rate which the vegetation achieves when the of moisture from the soil is not limiting. S is determined by the maximum transpiration rate that can be sustained under well-watered conditions.

b) Runoff generation

A simple bucket model (**Fig.1**) is used for runoff generation and no routing method is used in LPJ. The soil layer is treated as a simple bucket consisting of two layers with fixed thickness (upper 0.5m; lower 1.0m). Water content of both soil layers is updated daily, taking account of evapotranspiration, percolation and runoff. Since soil moisture spatial variability is not considered, runoff will not be generated until the soil is saturated across the basin, which is not the case for

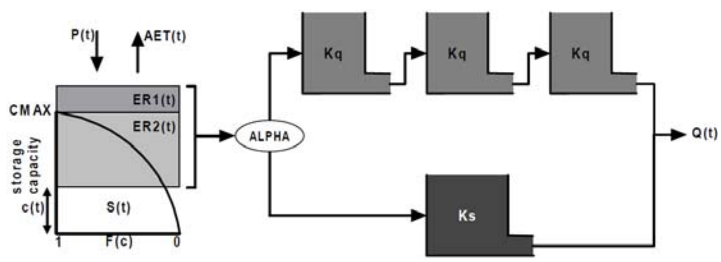

Fig.2 The HYMOD model structure. Effective rainfall ($ER1(t)$ and $ER2(t)$) is produced depending on the current catchment moisture state described by the storage capacity distribution function $F(c)$. The effective rainfall is distributed with respect to parameter ALPHA and either routed through three linear reservoirs with residence time Kq in series, or a single reservoir with residence time Ks.

Table 1 List of basin characteristics and data period for validation.

River system	Country	**Data period**	Area (km^2)	Annual rainfall(mm)	Aridity index	Max. NDVI
Angat	Philippines	**1987-1995**	781	3150	0.60	0.729
Haji	Japan	**1990-1998**	305	1800	0.61	0.809
Hushan	China	**1990-1998**	6374	2150	0.79	0.772
Todd	Australia	**1990-1998**	445	260	5.51	0.474

many basins. Therefore, modification is made to runoff generation mechanism by using HYMOD runoff generation and routing scheme (**Fig.2**)[9]. The HYMOD model assumes that the soil moisture storage capacity, c , varies across the catchment and, therefore, that the proportion of the catchment with saturated soils varies over time step t . The spatial variability of soil moisture capacity is described by the following distribution function:

$$F(c)=1-(1-c(t)/\mathrm{CMAX})^{\mathrm{BEXP}} \quad 0\le c(t)\le \mathrm{CMAX} \quad (3)$$

where CMAX is the maximum storage capacity and BEXP is the degree of spatial variability of soil moisture capacity.

Hereafter, the modified LPJ is referred to as LPJH in the following sections.

(2) Dataset

a) Study area

Four basins located in Philippines, Japan, China, and Australia were selected as the study area. The hydrological data of these basins was obtained under the collaboration with University of Yamanashi COE Virtual Academy (VA), Pristine Basin data, and Asian Pacific FRIEND. The main selection criteria were accessible hydrological data of good quality, long period, and the studied basins representing a variety of climate and vegetation conditions. Basic characteristics and the data period used in this study are listed in **Table 1**.

b) Model input and output

The LPJ and LPJH models were run for the period 1901-1998, preceded by a 1000-year spin-up period to reach an initial equilibrium with respect to carbon pools and vegetation cover from bare ground. The models were driven by grid (0.5° resolution) monthly precipitation, air temperature, and cloud cover from CRU TS 2.1[10], and by texture for nine soil types provided by FAO. Non-gridded model inputs include annual CO_2 concentrations (one global value) provided by the Carbon Cycle Model Linkage Project. Furthermore, various parameters are assigned to the different PFTs following Sitch *et al.*[6]. The parameters obtained from the optimized scheme developed by Li *et al.*[11] are forced to the LPJH model. Additionally, the LPJ and LPJH models were driven by in-site observed daily precipitation at the four basins for the periods listed in **Table 1**, the other input data keeping the same with the aforementioned run.

Table 2 Relative error for simulated runoff, where (Relative error = (Calculated Runoff – Observed runoff)/Observed runoff) for the simulated nine years at the four basins.

Relative error	LPJ(%)	LPJH(%)	HYMOD(%)
Angat	-16.03	-6.73	6.09
Haji	-25.89	-23.58	-11.96
Hushan	-20.03	-17.98	-1.90
Todd	-18.52	-11.21	-29.57

The output of the LPJ and LPJH models includes hydrological processes such as evapotranspiration and runoff at different time scales, vegetation characteristics such as LAI and fraction plant cover (FPC), as well as net primary production (NPP) and net ecosystem productivity (NEP) at annual scale.

c) Data for validation

Simulated runoff was compared with in-site observed data for the four basins at monthly and daily scales in terms of flow duration curves for the various periods listed in Table 1. It was also compared with runoff calculated from stand-alone hydrological model—the HYMOD model. Simulated FPC was compared with observed data from Japan Integrated Biodiversity Information System (J-IBIS) for the Haji basin in Japan, and from Global Land Cover Characterization (GLCC)

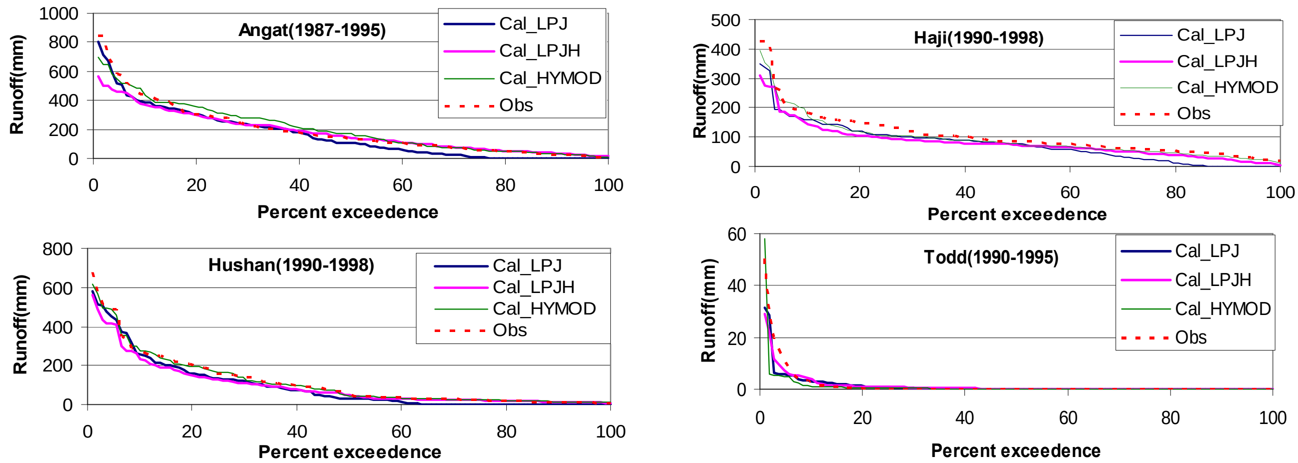

Fig.3 Observed and simulated monthly flow duration curves by the LPJ, LPJH and HYMOD models at the four basins.

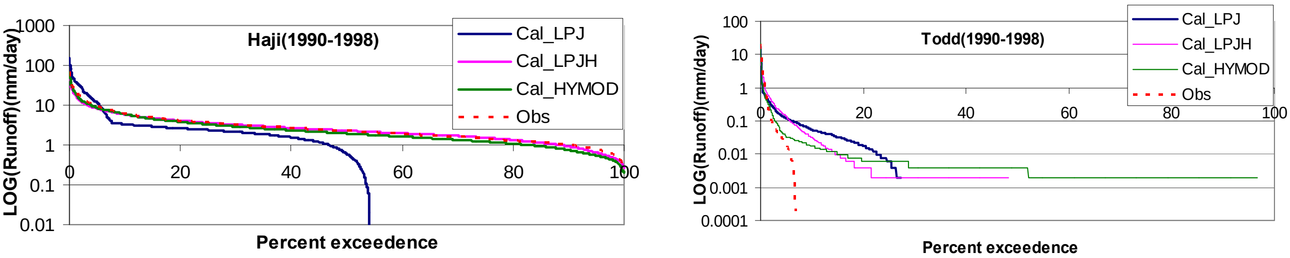

Fig.4 Observed and simulated daily flow duration curves by the LPJ, LPJH and HYMOD models for various periods at the four basins.

with International Geosphere Biosphere Programme (IGBP) classification for the other three basins. Simulated LAI was compared with the normalized difference of the vegetation index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR)[12]. LAI is an important surface biophysical parameter as a measure of vegetation cover and vegetation productivity; NDVI is an alternative measure of vegetation amount and conditions. Numerous studies have reported on the relationship between the NDVI and LAI.

(3) CO_2 scenario experiment

To explore the effects of vegetation on runoff at the basin scale under the changing climate conditions, and to show the potential advantages of LPJH over stand-alone hydrological models, the LPJH model was run under a scenario of changing atmospheric CO_2 content alone. Only the atmospheric CO_2 content for the historical period 1901-1998 including the spin-up was replaced by the B2 reference scenario for the period 2001-2098 calculated from ISAM model. As the values of CO_2 concentration were increased, plants increase their water use efficiency by transpiring less water per unit of carbon fixed[13]. Furthermore, vegetation is expected to be more productive, which may counteract the water savings due to decreased transpiration. In turn, the changes in transpiration rate, vegetation structure and production should feed back to soil water content and runoff generation. Since LPJH computes the dynamic relations among these processes, the net effect of increased atmospheric CO_2 concentration and of associated transient vegetation changes on the water balance can be quantified.

3. RESULTS AND DISCUSSION

(1) Model validation

The LPJ and LPJH models are validated in terms of monthly and daily runoff, average LAI, and vegetation type and composition for the periods (**Table 1**) where in-site observed precipitation and runoff data are available at the four basins. The simulated runoff by LPJ and LPJH models is also compared with the simulated runoff by the stand-alone hydrological model-HYMOD. This comparison may help to identify the advantages and disadvantages of DGVMs in simulating runoff over stand-alone hydrological models.

Compared with the monthly runoff simulated by the LPJ model, the monthly runoff simulated by LPJH agrees much better with observed runoff for the four basins, especially in the low flow period (**Fig.3 and Table 2**). This is attributable to the runoff generation mechanisms adopted in different models. All of the models underestimate runoff in the high flow period for all the study basins as well as the middle flow period except the HYMOD model for Angat basin in the Philippines. One possible reason for underestimate of runoff is that LPJ and LPJH consider only natural vegetation. Thereby simulated runoff should be low in regions where the model diagnoses a dominance of woody PFTs, although some parts of the land has converted into management land. For the Todd River basin in Australia, the LPJH model performs better than both the LPJ model and the HYMOD model. This is probably due to the high variability of vegetation in this basin. However, the HYMOD model cannot capture this variability of vegetation and the LPJ model cannot simulate the spatial soil moisture variability properly. Analogously, the LPJH model underestimates runoff in the high flow period at the daily scale. The LPJH model has an absolute advantage over the LPJ model and the simulated runoff by LPJH lie well with the HYMOD performance at the daily scale (only two basins' results are shown in **Fig.4**). Since the Todd River in Australia is a very arid basin, all of the models performed poorly in simulating daily runoff.

Annual LAI computed by LPJH is compared with annual maximum and accumulated values ($\sum NDVI$) of basin-averaged NDVI calculated from semi-monthly data. As discussed in Box *et al.*[14], $\sum NDVI$ has high correlation with biomass and can be used as an indicator for detecting inter-annual variability of vegetation activities. Here only the $\sum NDVI$ trend is shown with LAI trend in **Fig.5**. This figure indicates that the LAI trend calculated by LPJH agrees with $\sum NDVI$ trend for Angat basin in the validation years and for Haji basin in most of

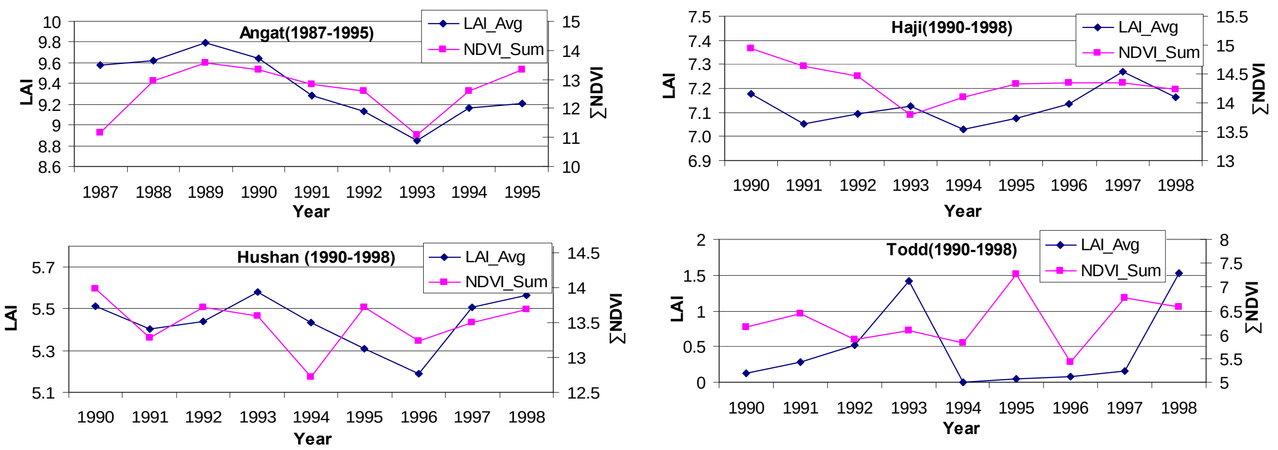

Fig.5 Trend comparison between $\sum NDVI$ values and LAI calculated by LPJH for various periods at the four basins.

the validation years. The LAI trend calculated by LPJH does not correspond so well with $\sum NDVI$ for Hushan basin, whereas correspond with maximum values of NDVI well. The LAI trend does not agree with NDVI trend in Todd River, which is probable attributable to the fact that LPJH does not consider shrub type plant functional types which are important in arid or semi-arid regions. Maximum values of NDVI indicates greening trend clearer while $\sum NDVI$ is more reliable for estimating biomass through the year. This trend correspondence demonstrates that LPJH can simulate vegetation biomass reasonably in humid basins.

Validation of simulated FPC is mainly performed in Haji river basin where detailed digital vegetation map (J-IBIS data) is available. The dominant plant types in the Haji basin derived from J-IBIS data are temperate broadleaved summergreen tree (referred to as TBS) and temperate needleleaved evergreen tree (referred to as TNE), with fractions being 46.1%, 23.7% respectively. The LPJH model provides the dominant plant functional types of TBS (52.8%) and TNE (42.2%), which corresponds to J-IBIS data mostly. For the other three study basins, the GLCC data with IGBP classification is used as a reference for validation of simulated FPC. Since the classification schemes are different between IGBP and LPJH, it is difficult to validate simulated FPC quantitatively. However, types of vegetation produced by LPJH are reasonably. For example, mixed forests are dominant for the Hushan basin derived from IGBP data, and three different PFTs (TNE, TBS, and temperate broadleaved summergreen tree, with each type taking about 30% of the basin area) are produced by LPJH.

(2) Results of CO_2 simulation experiment

Fig. 6 shows the changes in daily runoff caused by an increase in CO_2 content for the various periods at the four basins. Runoff increases by 11.9%, 11.8%, and 21.8% under this scenario in the Angat, Haji and Hushan basins respectively. In contrast, it decreases by 48.6% in the Todd River. These changes in runoff generation are mainly related to concurrent changes in transpiration. As a consequence of elevated CO_2, carbon assimilation rate increases and water loss through the stomata decreases. This effect is most pervasive in non-water limited environments, whereas in drier basins water stress restricts transpiration irrespective of ambient CO_2 concentration (Eq.(1)). The lower

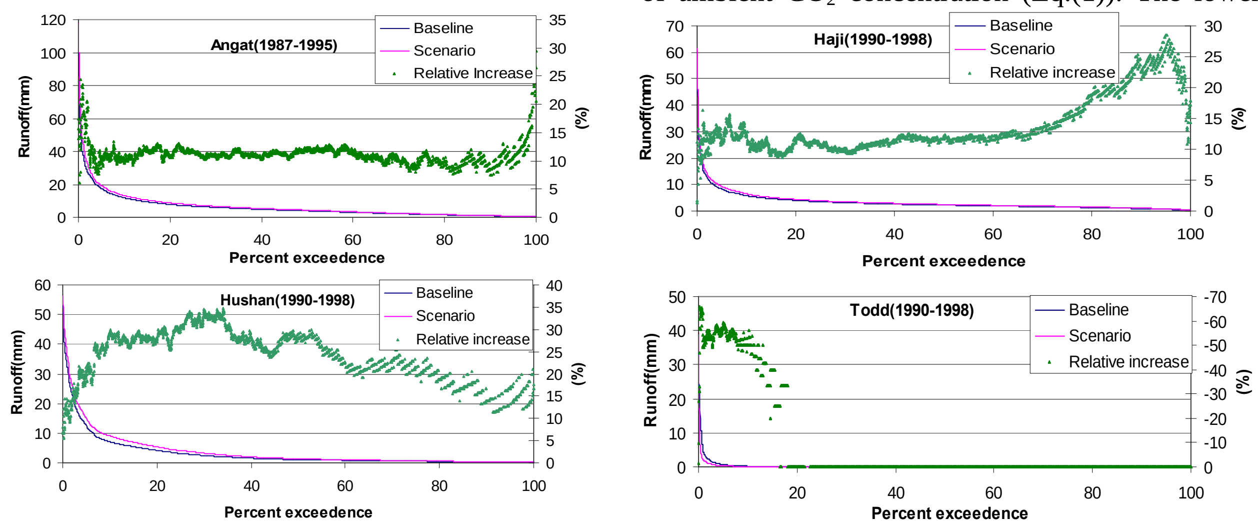

Fig.6 Change in daily runoff caused by increased atmospheric in CO_2 content for the various periods at the four basins. Y-axis on the right-hand side represents changes in daily runoff (%).

transpiration results in increased evaporation, as there is more water stored in the soil column. The runoff increase in the three basins located in humid regions suggests that reduced transpiration cannot be compensated for by soil evaporation. The significant runoff decreases in the Todd River basin is attributable to increased transpiration resulting from changing vegetation composition. **Fig.6** indicates that changes in runoff are greater for peak flow at the Angat, Haji and Todd River basin and greater for middle flow at the Hushan basin. The great changes for low flow at Angat and Haji basin is probably due to the fact that the low flow value itself is very small, thereby the relative increase may become high easily.

4. CONCLUSIONS

The simulation of dynamic interactions between vegetation and water is important for realistic assessment of water cycle. DGVMs are well suited tools for such biosphere-hydrosphere interrelations. The hydrological performance of a leading DGVM-LPJ is evaluated and improved by changing the runoff generation mechanism with the stand-alone hydrological model-HYMOD. The hydrological performance of LPJH is largely similar to that of stand-alone hydrological models at the basin scale. Moreover, the model produces reasonable vegetation type and composition in the humid basins while less reliable results in the arid basin. More basins having a wide variety of climate conditions should be included in order to evaluate the hydrological performance of LPJH comprehensively. Furthermore, the LPJH only produces natural vegetation type, which makes runoff generation unreliable.

The CO_2 simulation experiment demonstrates that the LPJH model has the capacity of exploring possible vegetation-driven changes such as runoff under the changing climate conditions at the basin scale. Similarly, reverse effects of changing hydrological conditions on vegetation can also be investigated, which is not considered in the present LPJH model.

In summary, the capacity of LPJH to simulate hydrological processes makes it a useful tool for examining impact of vegetation on runoff at basin scales. The potential advantage of LPJH over stand-alone hydrological models was clearly demonstrated by the CO_2 simulation experiment.

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REFERENCES

1) Gerten, D. *et al.*, Terrestrial vegetation and water balance—hydrological evaluation of a dynamic global vegetation model, *J. of Hydrol.*, Vol.286, pp.249–270, 2004.
2) Tague, C.L. and Band L.E., RHESSys: Regional Hydro-Ecologic Simulation System—An Object-Oriented Approach to Spatially Distributed Modeling of Carbon, Water, and Nutrient Cycling, *Earth Interactions*, Vol.8, Paper No. 19, 2004.
3) Oudin, L. *et al.*, Has land cover a significant impact on mean annual streamflow? An international assessment using 1508 catchments, *J. of Hydrol.*, Vol.357, pp.303–316, 2008.
4) Donohue, R. J., Roderick, M. L., and McVicar, T. R., On the importance of including vegetation dynamics in Budyko's hydrological model. *Hydrol. Earth Syst. Sci.*, Vol.11, pp.983–995, 2007.
5) Neilson, R.P. and Marks, D., A model for predicting continental-scale vegetation distribution and water balance. *Ecol. Appl.* , Vol.5, pp.362-386, 1995.
6) Sitch, S. *et al.*, Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Glob. Change Biol.*, Vol.9, pp.161-185, 2003.
7) Haxeltine, A. and Prentice, I. C., BIOME3: An Equilibrium Terrestrial Biosphere Model Based on Ecophysiological Constraints, Resource Availability, and Competition Among Plant Functional Types, *Global Biogeochem. Cycles*, Vol.10(4), pp.693–709, 1996.
8) Monteith, J.L., Accommodation between transpiring vegetation and the convective boundary layer. *J. Hydrol.* Vol.166, pp.251–263, 1995.
9) Wagener, T. *et al.*, A framework for development and application of hydrological models, *Hydrol. Earth Syst. Sci.*, Vol.5(1), pp.13–26, 2001.
10) Mitchell, T.D., An improved method of constructing a database of monthly climate observations and associated high resolution grids, *Int. J. Climatol.* Vol. 25, pp.693–712, 2005
11) Li, Q.L., Ishidaira, H., and Bastola, S., intercomparison of hydrological modeling performance with multi-objective optimization algorithm in different climates, *Annual Journal of Hydraulic Engineering*, JSCE, Vol.53, pp.19-24, 2009.
12) Pizon, J., Brown, M.E., and Tucker, C. J., Satellite time series correction of orbital drift artifacts using empirical mode decomposition. In: N. Huang (Editor), Hilbert-Huang Transform: *Introduction and Applications*, pp. 167-186. 2005.
13) Lockwood, J.G., Is potential evapotranspiration and its relationship with actual evapotranspiration sensitive to elevated atmospheric CO_2 levels? *Clim. Change*, Vol.41, pp.193–212, 1999.
14) Box, E. O., Holben, B.N., and Kalb, V., Accuracy of the AVHRR vegetation index as a predictor of biomass, primary productivity and net CO_2 flux, *Vegetatio*, Vol.80, pp.71-89, 1989.

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