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Effects of future climate change, CO_2 enrichment, and vegetation structure variation on hydrological processes in China

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ABSTRACT

Investigating the relationship between factors (climate change, atmospheric CO_2 concentrations enrichment, and vegetation structure) and hydrological processes is important for understanding and predicting the interaction between the hydrosphere and biosphere. The Integrated Biosphere Simulator (IBIS) was used to evaluate the effects of climate change, rising CO_2, and vegetation structure on hydrological processes in China at the end of the 21st century. Seven simulations were implemented using the assemblage of the IPCC climate and CO_2 concentration scenarios, SRES A2 and SRES B1. Analysis results suggest that (1) climate change will have increasing effects on runoff, evapotranspiration (ET), transpiration (T), and transpiration ratio (transpiration/evapotranspiration, T/E) in most hydrological regions of China except in the southernmost regions; (2) elevated CO_2 concentrations will have increasing effects on runoff at the national scale, but at the hydrological region scale, the physiology effects induced by elevated CO_2 concentration will depend on the vegetation types, climate conditions, and geographical background information with noticeable decreasing effects shown in the arid Inland region of China; (3) leaf area index (LAI) compensation effect and stomatal closure effect are the dominant factors on runoff in the arid Inland region and southern moist hydrological regions, respectively; (4) the magnitudes of climate change (especially the changing precipitation pattern) effects on the water cycle are much larger than those of the elevated CO_2 concentration effects; however, increasing CO_2 concentration will be one of the most important modifiers to the water cycle; (5) the water resource condition will be improved in northern China but depressed in southernmost China under the IPCC climate change scenarios, SRES A2 and SRES B1.
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1. Introduction

Climate change is expected to have significant impacts on world water resources (Falloon and Betts, 2006; Gerten et al., 2007; IPCC, 2007). Effects on evaporation and precipitation due to climate change will accelerate water cycles (Del Genio et al., 1991; Arnell, 2001; Huntington, 2006; Liu et al., 2008); consequently, the rate of available renewable freshwater resources may be enhanced (Oki and Kanae, 2006). Discharge of river flow is a useful indicator for freshwater availability (Falloon and Betts, 2006). The average annual discharge of freshwater of the six largest Eurasian rivers that flows to the Arctic Ocean increased by 7% in the last century because of changes to the North Atlantic Oscillation and global mean surface air temperature (Peterson et al., 2002). Analysis also showed that river discharges have been more sensitive to climate change than to natural climate variability over the last 9000 years (Aerts et al., 2006).

According to the stomatal conductance optimization hypothesis, the plant stomata are simultaneously maximizing the carbon gain rate while minimizing the rate of water loss (Katul et al., 2009), and plants tend to reduce stomatal conductance and suppress transpiration under high CO_2 concentration (Collatz et al., 1992; Field et al., 1995). Current experimental and modeling evidence suggests that increasing CO_2 concentration will improve water use efficiency of plants (Gerten et al., 2007; Zhu et al., 2011b). CO_2-induced changes in canopy transpiration affects evapotranspiration (ET) and latent heat flux to the

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atmosphere, such as reducing water loss, and may have profound impacts on the hydrological cycle (Sellers, 1996; Robock and Li, 2006; Cao et al., 2009). The effect of altered CO_2 concentration on runoff is a central concern of the climate change research field (Field et al., 1995). However, the magnitude and importance of CO_2-induced effects on runoff are in dispute. Some studies argued that CO_2 is likely to be a significant factor in the water balance even of relatively wet regions especially for sub-regional spatial scales and seasonal time scales (Kruijt et al., 2008) and that ecosystems are less water limited than anticipated because of the physiological vegetation response to elevated CO_2 (Gerten et al., 2007). Gedney et al. (2006) pointed out that the increasing trend of continental runoff through the 20th century is mainly due to suppression of plant transpiration as a consequence of CO_2-induced stomatal closure. At the same time, many studies challenged Gedney's perspective (Peel and McMahon, 2006; Chaplot, 2007; Piao et al., 2007; Huntington, 2008). Huntington (2008) argued against the physiological CO_2 effect on runoff during the 20th century. After investigating the interactions of CO_2, temperature, and precipitation on runoff, Luo et al. (2008) found only a small increase in runoff driven by the physiological effects of CO_2 concentration. Therefore, the investigation of the relationship between runoff and CO_2 concentration is important for understanding how climate change affects the hydrological cycle (Allen and Ingram, 2002). Determining the hydrological responses of terrestrial ecosystems to elevated CO_2 concentration is also critical for predicting ecosystem and landscape processes (Hungate, 2002).

Higher CO_2 concentration levels can also enhance the photosynthetic rate, known as the CO_2 fertilization effect (Ball et al., 1986), which leads to greater leaf area index (LAI) and changes the vegetation distribution (Betts et al., 1997; Levis et al., 2000; Felzer et al., 2009). Increased LAI in elevated CO_2 concentration can reduce the radiation reaching the soil surface, thereby reducing soil evaporation (Hungate, 2002), and the vegetation feedback can further accelerate the hydrological cycle (Alo and Wang, 2008). Because the extent of the net effect of physiological and structural vegetation on water balances at local and global scales due to CO_2 enrichment is still under debate (Leipprand and Gerten, 2006), the effects of elevated CO_2 concentration on water cycles requires quantification of both physiological and structural vegetation dynamics (Piao et al., 2007). Structural changes in vegetation imply modifications in land surface properties such as albedo, stomatal resistance, and LAI (Foley et al., 2000). The composition and distribution of plant communities are of fundamental importance for ET and runoff generation (Gerten et al., 2004), so the change in runoff can not only be explained by changing precipitation but can also be driven by dynamics of vegetation composition and distribution (Cramer et al., 2001).

On the one hand, it is still largely unknown if the vegetation structure response to climate change could alter the hydrological processes (Alo and Wang, 2008). Also the long-term and large-scale net effect of elevated CO_2 concentration on the terrestrial water balance remains uncertain (Gerten et al., 2007). On the other hand, it is relatively expensive to explore the interactive effects of multiple global factors on ecosystem processes in manipulative experiments (Luo et al., 2008). Furthermore, although stand-alone hydrological models can simulate the details of hydrological processes, they lack mechanistic links between the biosphere (e.g., plant transpiration to atmospheric CO_2) and the hydrosphere (e.g., soil moisture and runoff generation) (Gerten et al., 2004). For example, some earlier studies with stand-alone hydrological models probably overestimated CO_2 effects (Leipprand and Gerten, 2006), and some studies based on observed data lack an assessment of the sensitivity of river discharge to long-term climate change because discharge measurements cover a limited time span (Aerts et al., 2006). Leipprand and Gerten (2006) pointed out that physiological and structural responses of plants to changes in CO_2 concentration should be considered in a dynamic manner. The dynamic global vegetation model (DGVM) is a powerful tool to simulate the coupled processes of terrestrial carbon and water cycles at large temporal and spatial scales.

Climate change and its impacts on water resources have become a major force which China will have to cope with (Piao et al., 2010). As a DGVM, the Integrated Biosphere Simulator (IBIS, (Foley et al., 1996)) was used in this study to investigate the direct and indirect effects of climate change, elevated CO_2 concentrations and vegetation structure on hydrological process of China at the end of 21st century in this study. The primary objectives were 1) to evaluate the effects of climate change and elevated CO_2 concentrations on hydrological parameters (runoff, evapotranspiration, transpiration, and transpiration ratio (transpiration/evapotranspiration, T/E)); 2) to study the vegetation structure variation under climate change and elevated CO_2 concentration conditions and how they affect runoff; and 3) to explore the difference and importance of effects on hydrological processes in China caused by climate change, elevated CO_2 concentrations, and vegetation structure variation at the end of 21st century.

2. Methods and materials

2.1. Model description

IBIS is designed to integrate a variety of terrestrial ecosystem phenomena within a single, physically consistent modeling framework. It represents land surface processes, canopy physiology, vegetation phenology, long-term vegetation dynamics, and carbon cycling (Foley et al., 1996; Kucharik et al., 2000; Coe et al., 2002).

The hydrological module in IBIS is constructed based on a land-surface-transfer scheme (LSX) (Thompson and Pollard, 1995a, b). Two canopy layers, three snow layers, and six soil layers are considered in each grid unit. Total runoff is expressed as the difference between precipitation and the sum of evapotranspiration and water storage (Twine et al., 2004). The total amount of evapotranspiration from the land surface is defined as the sum of three water vapor fluxes: evaporation from the soil surface (including ice and snow), evaporation of water intercepted by vegetation canopies, and canopy transpiration. Rates of transpiration depend on canopy conductance and are calculated independently for each plant type within the canopy (Foley et al., 1996; Kucharik et al., 2000). Evaporation rates are calculated using standard mass transfer equations relating the temperature of the surface, vapor pressure deficit, and conductance (Campbell and Norman, 1998; Twine et al., 2004).

IBIS represents natural vegetation using plant functional types (PFT) which is characterized in terms of biomass and LAI. For each PFT, IBIS adopts a mechanistic treatment of canopy photosynthesis based on Farquhar et al. (1980) and Farquhar and Sharkey (1982), and a semi-mechanistic model of stomatal conductance (Ball et al., 1986; Foley et al., 1996; Kucharik et al., 2000) to quantify the gross primary productivity (GPP). LAI is expressed in terms of carbon in leaves and specific leaf area for upper and lower canopy (specified for each PFT) (Kucharik et al., 2000). A dynamic vegetation mechanism is adopted to simulate changes in vegetation structure on an annual time step through PFT competition for light and water from common resource pools. (Kucharik et al., 2006). The competition between PFTs is depended on the differences of resource availability, carbon allocation, phenology, leaf-form, and photosynthetic pathway (Foley et al., 1996; Kucharik et al., 2000). The phenology process is simulated using relationships between accumulated growing degree-days and budburst (Kucharik et al., 2006).

2.2. Study region and model forcing data

A 0.085-degree (~10-km) resolution land mask map of China was used in the IBIS simulations. The map excluded water bodies and the northwestern region with saline crusts that lacks soil information. A hole-filled version of the Shuttle Radar Topography Mission (SRTM)

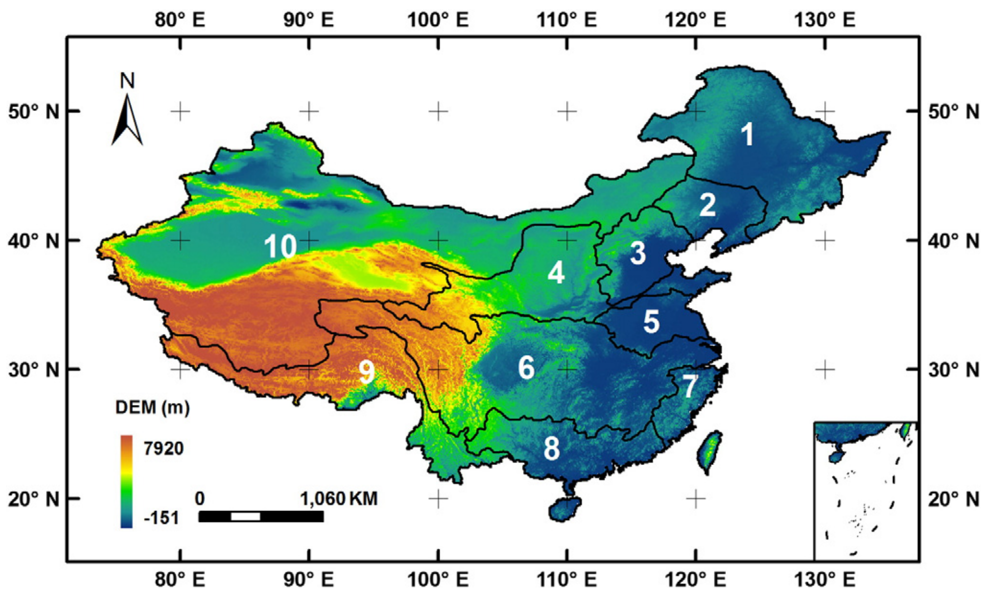

Fig. 1. DEM map of China and the hydrological regions of China: 1: Heilongjiang, 2: Liaohe, 3: Haihe, 4: Yellow River, 5: Huaihe, 6: Yangtze River, 7: Zhemin, 8: Zhujiang, 9: Southwest, 10: Inland.

Digital Elevation Model (DEM) dataset (Jarvis et al., 2006) for China was re-sampled to 0.085-degree resolution (Fig. 1) as input topographic data. The 1:1,000,000 China soil map provides the fractions of sand, clay, and silt for each soil layer and each cell(Shi et al., 2004). The 1:4,000,000 China vegetation map was reclassified into IBIS specific vegetation types for simulation initialization(Hou et al., 1979). A land cover map of China for 2000 (1-km resolution) (Data Center for Resources and Environmental Sciences Chinese Academy of Sciences (RESDC), 2001) was used to construct a vegetation cover fraction layer for each grid cell, allowing a more detailed representation of the current land use and land cover condition in the simulation.

Two projected future climate datasets under IPCC SRES scenarios (A2 and B1), which were developed for the Third Assessment Report (Nakicenovic and Swart, 2000) and used for the Fourth Assessment Report (AR4) of the IPCC (2007), were selected from the third version of the Canadian Centre for Climate Modeling and Analysis (CCCMA) Coupled Global Climate Model (CGCM3.1). Emission scenarios SRES A2 and SRES B1 represent high and low emission level respectively in this study. Averaged observed meteorological data (precipitation, air temperature, relative humidity, and cloudiness fraction) from 1950 to 2006 were used as a baseline climate condition. CO_2 concentration was constructed in each year for scenarios SRES A2 and SRES B1. In 2100, the CO_2 concentration is projected to increase to 836 ppmv under scenario SRES A2 and to 540 ppmv under scenario SRES B1 (Table 1) (IPCC, 2001). Detailed information about forcing data and CO_2 concentration construction is described in Zhu et al. (2011b).

Table 1
List of simulation scenarios performed; NOCC: applying the mean climatic data from 1950 to 2006; CCO_2: constant CO_2; DCO_2: elevated CO_2; 385 ppmv: 2008 CO_2 concentrations.

Scenarios	Climatic data	CO_2 concentration (2009–2099)
NOCC and CCO_2	NOCC	385 ppmv
NOCC and DCO_2(A2)	NOCC	SRES A2 (385–835 ppmv)
NOCC and DCO_2(B1)	NOCC	SRES B1 (385–540 ppmv)
A2 and CCO_2	SRES A2 (CGCM3)	385 ppmv
A2 and DCO_2(A2)	SRES A2 (CGCM3)	SRES A2 (385–835 ppmv)
B1 and CCO_2	SRES B1 (CGCM3)	385 ppmv
B1 and DCO_2(B1)	SRES B1 (CGCM3)	SRES B1 (385–540 ppmv)

2.3. Simulations and model validation

Seven comparable simulations were conducted under different climate change and CO_2 concentration scenarios (Table 1). Simulations were performed with projected climate data, soil texture, and initial vegetation conditions. The simulation results from 1950 to 2099 were selected for current and future periods analysis.

IBIS has been widely tested at different spatial scales and in different ecosystems for carbon and water cycling investigation (Foley et al., 1996, 2000; Kucharik et al., 2000, 2006). From our previous studies using IBIS in China: simulated runoff captured 85% of the spatial variability and 80% of the temporal variability for 85 hydrological gages (with 39 years of observed data) across China; the Nash–Sutcliffe coefficients indicated that the quantity pattern of runoff was captured quite well; the simulated ET matched reasonably with estimated ET that is calculated as the residual of observed precipitation and runoff (Zhu et al., 2010b). Comparison between the observed (about 40 stations with monthly observed data from 1981 to 1999) and simulated soil moisture shows that mean errors are within 10% for all the months and root mean squared errors are within 10% for most of the seasons (Zhu et al., 2009). Validation for soil temperature simulation based on 650 stations observed data (from 1955 to 2000) shows that IBIS model performs well in capturing spatial and temporal patterns of soil temperature (Zhu et al., 2010a). Validation and comparison showed reasonable agreement for variables related to carbon exchange processes using forestry inventory data (for net primary productivity and biomass validation), flux site data (for gross primary productivity validation), and literature reported data (for net primary productivity and biomass validation) at regional (Zhu et al., 2011a) and national (Zhu et al., 2011b) scales.

2.4. Data analysis method

The percentage changes of runoff, ET, transpiration, T/E, and LAI were calculated as:

$$\text{Increased percentage} = (V_{II} - V_I)/V_I * 100\%$$

where V represents the variables of runoff, ET, transpiration, T/E, and LAI; the subscript II represents the mean value of the end period of the 21st century (2080–2099); and the subscript I represents the

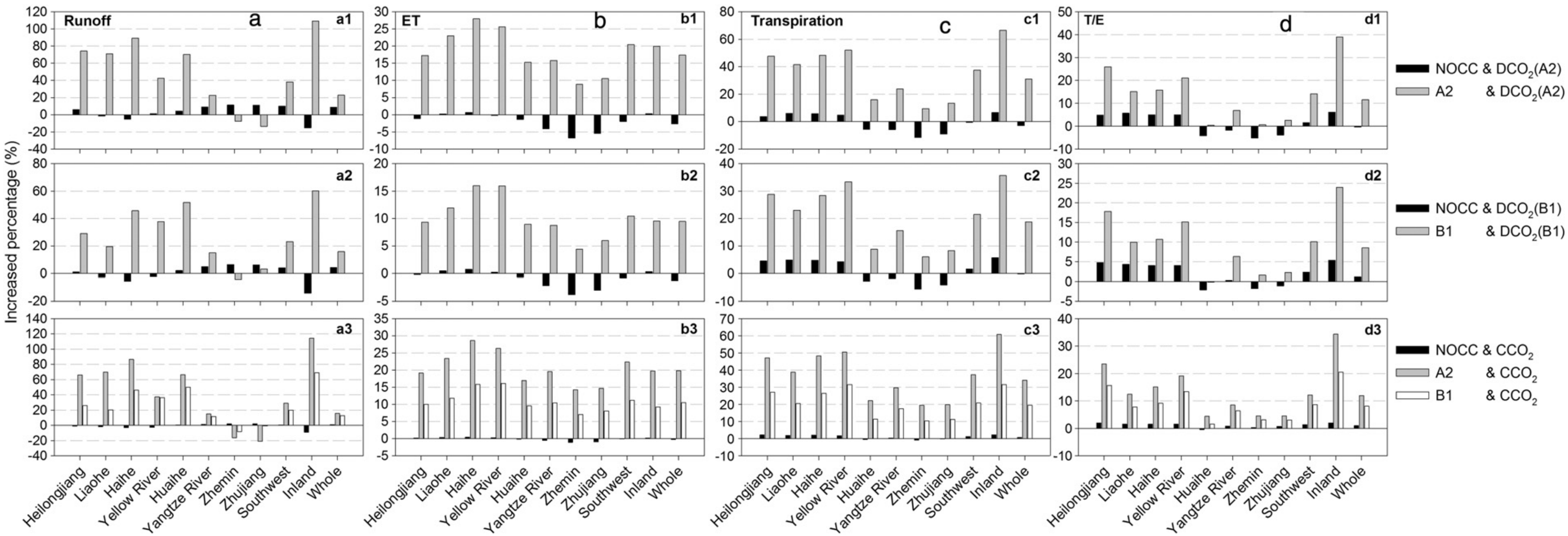

Fig. 2. Relative change caused by climate change by 2080–2099 compared to the baseline of 1950–2008 in a) runoff, b) Evapotranspiration (ET), c) transpiration (T), d) T/E.

mean value of the historical period 1950–2008. Different comparisons were made between different scenarios to evaluate the effects of climate change, elevated CO_2 concentration, or vegetation structure on the water budget of China. LAI was used as the indicator of vegetation structure in this study. Among these variables, T/E is rarely studied on a large scale (Liu, 2009). In this study, most analysis is based on hydrological regions scale which are divided according to the hydrological yearbook of China (Fig. 1) (Ministry of Water Resources of the People's Republic of China, 2000).

3. Results

The baseline simulation showed that runoff, ET, T, and T/E in southern regions is at highest level with regional averages about 500–700 mm, 900–1000 mm, 500–650 mm, and 0.6, respectively. The Inland region showed the lowest level for runoff, ET, T, and T/E with averages about 7 mm, 170 mm, 43 mm, and 0.25 respectively. Regional averages for the northern part of China (regions 1 to 4, Fig. 1) are about 50–100 mm, 400–450 mm, 150–250 mm, and 0.4–0.47 for runoff, ET, T, and T/E respectively.

3.1. Evaluating the effects of climate change

To highlight the effects of climate change, comparisons were made between scenarios with climate change and scenarios without climate change (Figs. 2–4).

3.1.1. Runoff

The mean runoff of the whole country showed a slight increase without climate change, but considerable increase under climate change conditions (Fig. 2a).

In view of hydrological regions, runoff will be enhanced significantly in northern and in central northern China under climate change conditions (Fig. 4, Table 2). The most significant increasing effect on runoff was shown in the Inland region under both SRES A2 and SRES B1 climate scenarios (Fig. 4, Table 2). Decreasing effects of climate change on runoff were found in southern China (Zhemin region and Zhujiang region, Fig. 4, Table 2).

In northern regions, slight decreasing trends for runoff were shown without climate change. However, climate changes will result in a compensation for the decrease in runoff, with a significant enhancement in these northern regions (Fig. 2a). This pattern is especially considerable in the Inland region (Fig. 2a). In contrast, in southeastern regions, a slight increase in runoff is shown under no climate change conditions, whereas climate change will eliminate these increasing effects and result in decreasing effects on runoff (Fig. 2a, Table 2).

At the national level, climate change will increase runoff at the end of the 21st century by approximately 14% and 11% relative to the 1950–2008 period under the SRES A2 and SRES B1 scenarios, respectively (Table 2). Falloon and Betts (2006) predicted that the average global total river flow for 2071–2100 will increase approximately 4% and 8% relative to 1961–1990 under the A1B and SRES A2 scenarios, respectively. The average river flow of the Yangtze River is projected to increase by approximately 19% and 16.3% under the A1B and SRES A2 scenarios, respectively. Our results suggested that the Yangtze River runoff will be enhanced by approximately 13% and 10% under the SRES A2 and SRES B1 climate scenarios, respectively.

3.1.2. Evapotranspiration (ET)

Climate change results in increasing effects on ET in each hydrological region and countrywide (Fig. 4). The increasing effects in northern China are greater than those in southern China (Fig. 2b), especially in the Haihe and Yellow River regions. The increasing rates for these two regions were above 25% and 15% under the SRES A2 and SRES B1 climate scenarios, respectively (Fig. 2b).

Under the no climate change scenarios (NOCC and DCO_2 (A2), NOCC and DCO_2 (B1), and NOCC and CCO_2), ET decreases at the national scale with decreasing trends mainly in southern regions (Yangtze River, Zhemin, Zhujiang) (Fig. 2b).

3.1.3. Transpiration

Climate change shows increasing effects on transpiration for the whole country at the end of the 21st century as well as for each hydrological region (Fig. 4). The mean increasing rates in the northern regions are higher than in the southern regions (Fig. 4). The transpiration of the Inland region is more sensitive to climate change than other regions with an increase more than 60% and 30% under the SRES A2 and SRES B1 scenarios, respectively (Fig. 2c). Under scenarios in which climate change is not a factor, transpiration showed a slight increase in the northern regions and a slight decrease in most southern regions (Fig. 2c).

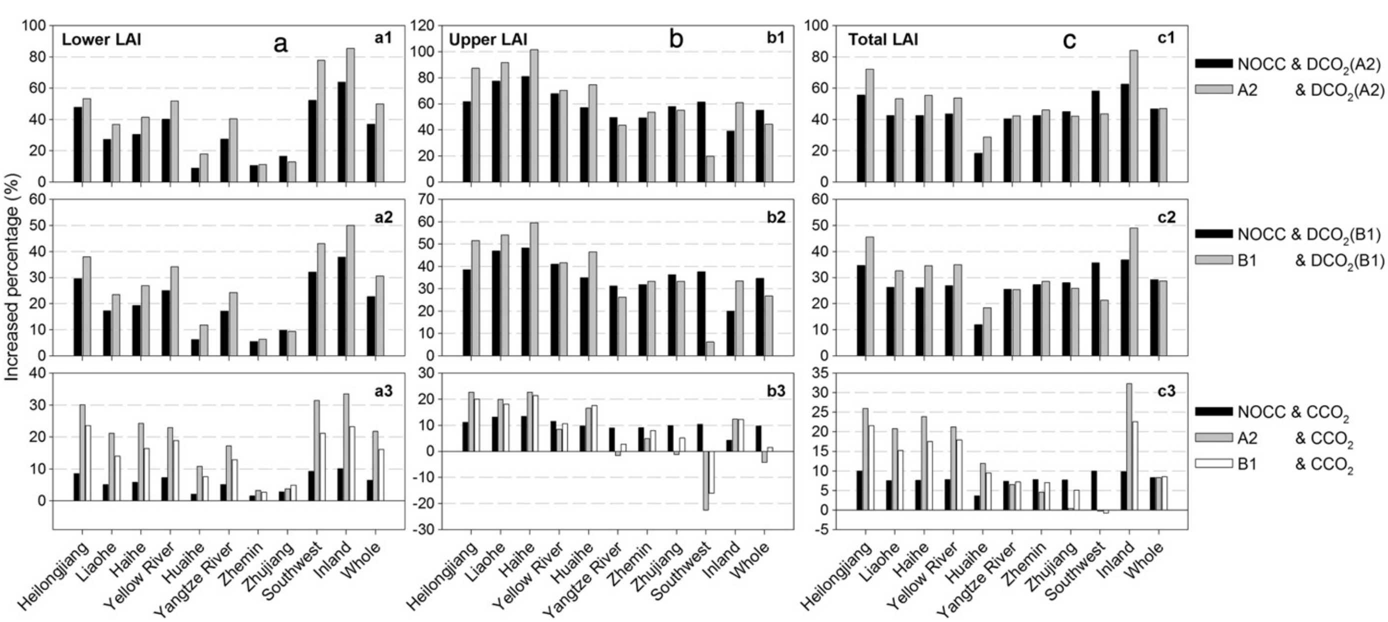

Fig. 3. Relative change caused by climate change on vegetation structure by 2080–2099 compared to the baseline of 1950–2008 a) lower LAI, b) upper LAI, c) total LAI.

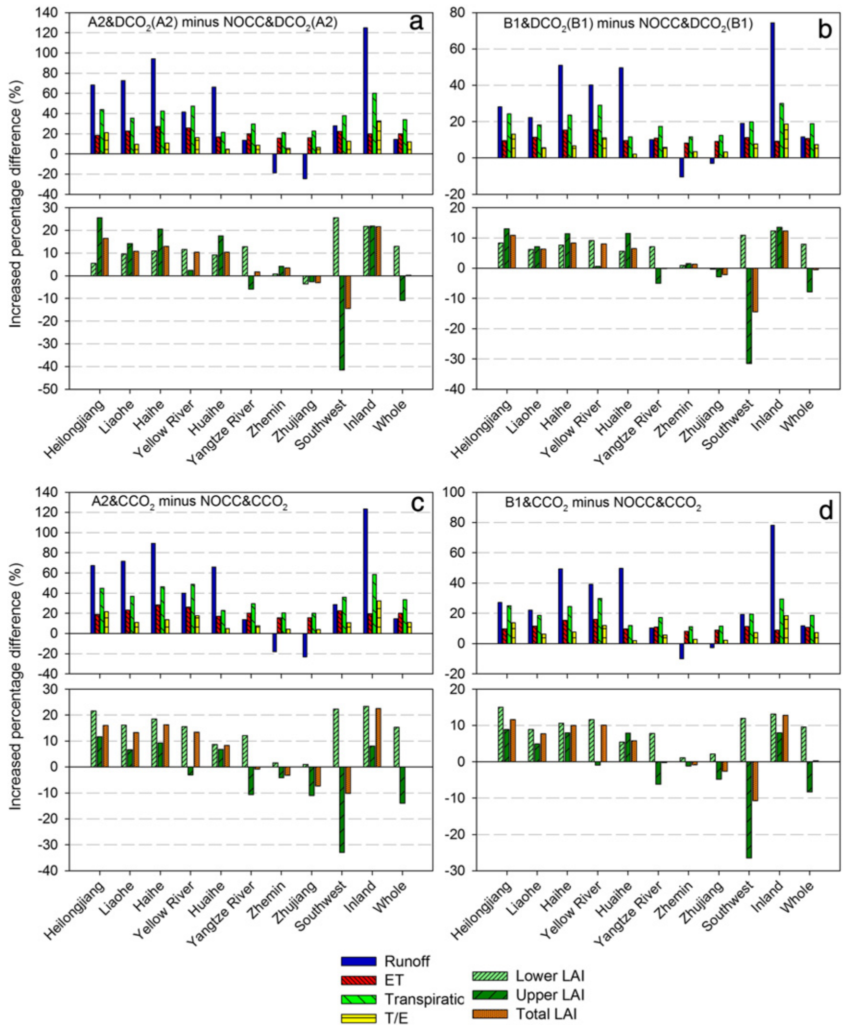

Fig. 4. Effect size of climate change for runoff-related variables calculated by differences between scenarios with and without climate change. a. A2 and DCO_2(A2) and NOCC and DCO_2(A2), b. B1 and DCO_2(B1) and NOCC and DCO_2(B1), c. A2 and CCO_2 and NOCC and CCO_2, d. B1 and CCO_2 and NOCC and CCO_2.

3.1.4. Transpiration/Evapotranspiration (T/E)

The increasing effects of climate change on T/E are similar to the pattern on transpiration. T/E is projected to be enhanced at the country scale due to climate change effects with a higher increase rate in northern China than in southern China. The T/E will be most sensitive to climate change in the Inland region (Fig. 2d).

As a whole, Fig. 4 indicates that climate change will have increasing effects on ET, transpiration, and transpiration ratio (T/E) at the country scale and in different hydrological regions. All these variables are more sensitive to climate change in northern China than in southern China.

Table 2
Relative change of runoff by the end of 21st century caused by climate change in the hydrological regions of China.

Regions	Effects of climate change (%)			
	SRES A2 (elevated CO_2)	SRES B1 (elevated CO_2)	SRES A2 (constant CO_2)	SRES B1 (constant CO_2)
Heilongjiang	+68.3	+28.1	+67.2	+27.1
Liaohe	+72.7	+22.3	+71.5	+22.0
Haihe	+94.3	+51.0	+89.4	+49.3
Yellow River	+41.4	+40.1	+40.0	+39.1
Huaihe	+66.2	+49.6	+65.9	+49.7
Yangtze River	+13.4	+10.1	+13.7	+10.4
Zhemin	−18.9	−10.5	−18.1	−10.1
Zhujiang	−24.6	−3.0	−23.0	−2.6
Southwest	+27.9	+19.1	+28.6	+19.3
Inland	+124.9	+74.4	+123.4	+78.1
Whole country	+14.3	+11.6	+14.7	+11.8

3.2. Evaluating the effects of CO_2 concentration enrichment

In order to investigate the effects of CO_2 concentration enrichment, comparisons were made for runoff, ET, transpiration, T/E, and LAI between scenarios under elevated CO_2 concentrations and constant CO_2 concentrations (Figs. 5–7).

3.2.1. Runoff

Elevated CO_2 concentration shows increasing effects on runoff at the country scale (Figs. 5a, 7). The elevated CO_2 is projected to increase runoff at the end of the 21st century by approximately 7% and 3% relative to the 1950–2008 period under the SRES A2 and SRES B1 scenarios, respectively. (Fig. 7, Table 3).

At the hydrological region scale, elevated CO_2 concentration has significant decreasing effects on runoff in the Inland region (Figs. 5a, 7, Table 3). Significant increasing effects of elevated CO_2 concentrations on runoff are projected in the southern hydrological regions and the Heilongjiang region (Fig. 7). The positive effects of elevated CO_2 would compensate the decreasing runoff in the Zhenmin and Zhujiang regions under both SRES A2 and SRES B1 CO_2 scenarios with climate change.

Globally, many studies show that runoff would be enhanced under elevated CO_2 concentrations and most of the increasing rates are

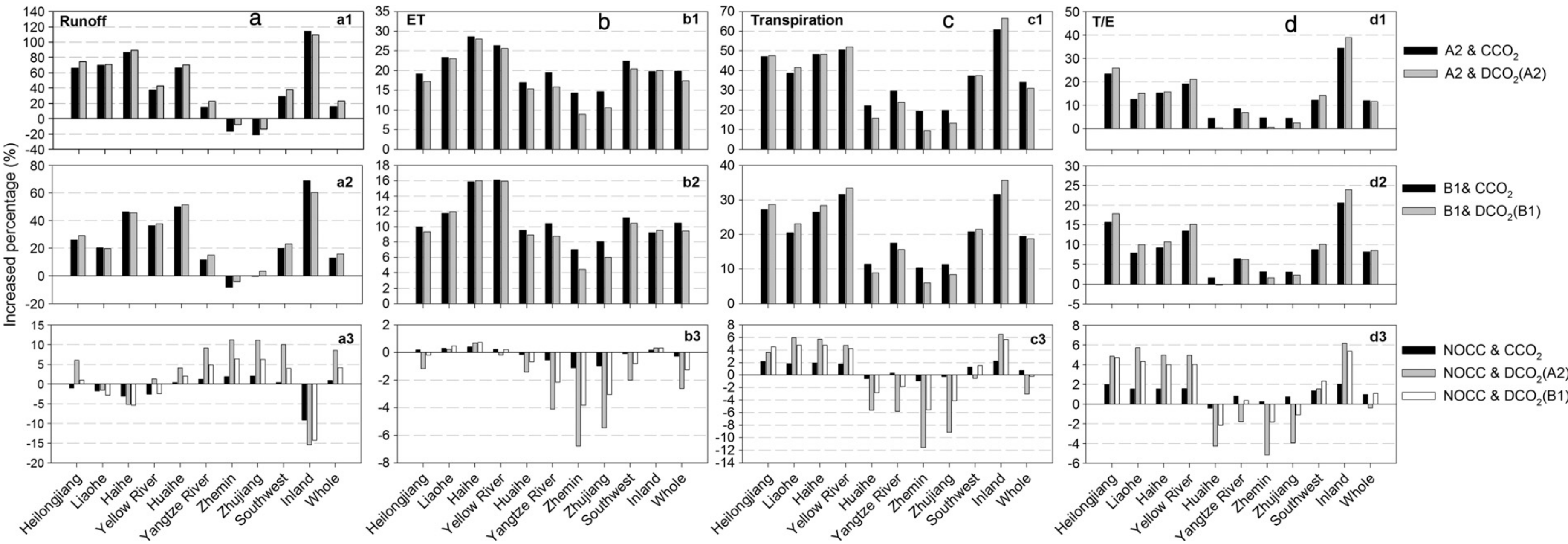

Fig. 5. Relative change caused by increasing CO2 concentration by 2080–2099 compared to the baseline of 1950–2008 in a) runoff, b) Evapotranspiration (ET), c) transpiration (T), d) T/E.

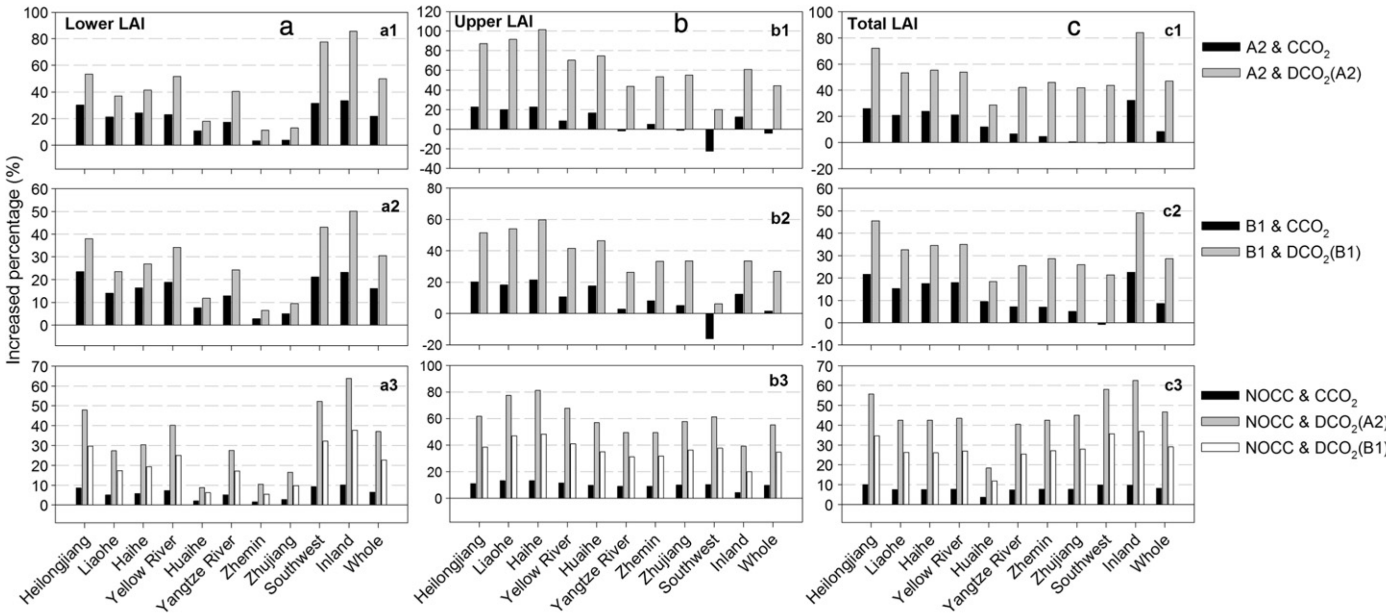

Fig. 6. Relative change caused by increasing CO2 concentration on vegetation structure by 2080–2099 compared to the baseline of 1950–2008 a) lower LAI, b) upper LAI, c) total LAI.

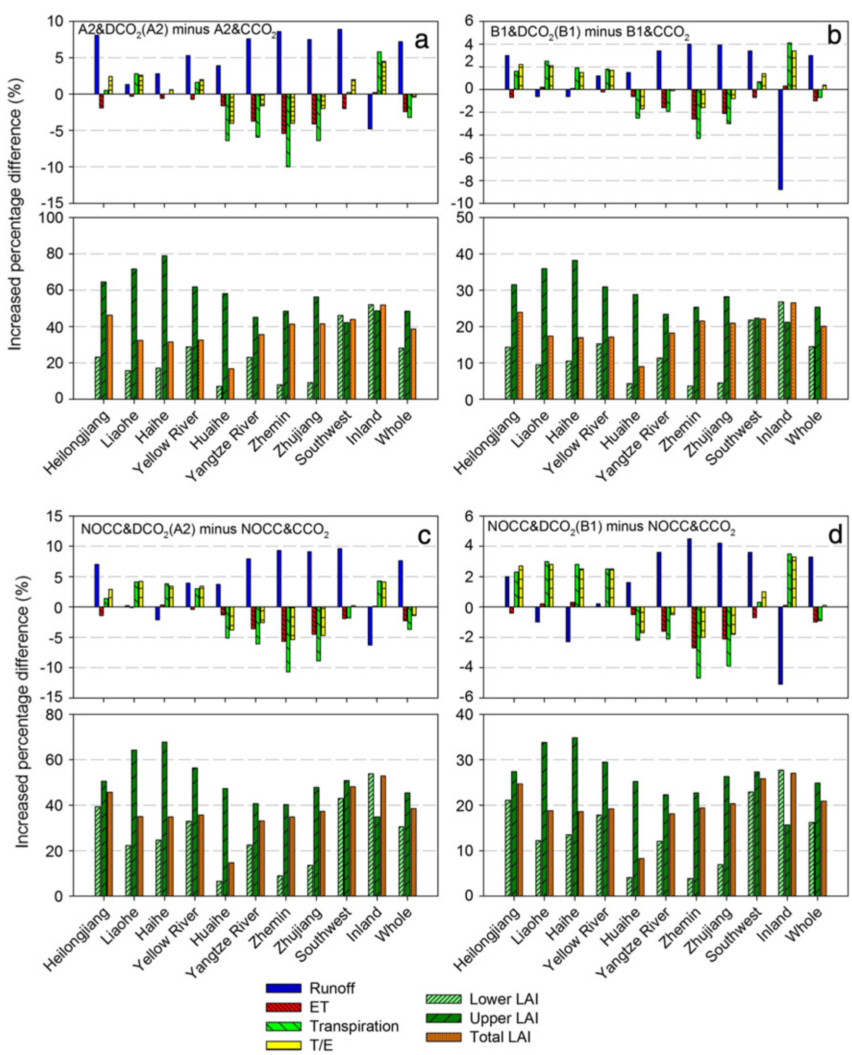

Fig. 7. Effect size of increasing CO2 concentration for runoff-related variables calculated by differences between scenarios with and without climate change: a. A2 and DCO_2(A2) and A2 and CCO_2, b. B1 and DCO_2(B1) and B1 and CCO_2, c. NOCC and DCO_2(A2) and NOCC and CCO_2, d. NOCC and DCO_2(B1) and NOCC and CCO_2.

Table 3
Relative change of runoff by the end of 21st century caused by increase in CO_2 concentration in the hydrological regions of China (CC: climate change).

Regions	Effects of elevated CO_2 concentration (%)			
	SRES A2 (with CC)	SRES B1 (with CC)	SRES A2 (without CC)	SRES B1 (without CC)
1. Heilongjiang	+8.1	+3.0	+7.0	+2.0
2. Liaohe	+1.3	−0.6	+0.2	−1.0
3. Haihe	+2.8	−0.6	−2.1	−2.3
4. Yellow River	+5.3	+1.2	+3.9	+0.2
5. Huaihe	+3.9	+1.5	+3.7	+1.6
6. Yangtze River	+7.6	+3.4	+7.9	+3.6
7. Zhemin	+8.6	+4.0	+9.3	+4.5
8. Zhujiang	+7.5	+3.9	+9.1	+4.2
9. Southwest	+8.9	+3.4	+9.6	+3.6
10. Inland	−4.8	−8.8	−6.3	−5.1
Whole country	+7.2	+3.0	+7.6	+3.3
Range	−4.8 to +8.9	−8.8 to +4.0	−6.3 to +9.6	−5.1 to +4.5

within 10% (Neilson and Marks, 1994; Cramer et al., 2001; Gerten et al., 2004, 2008; Leipprand and Gerten, 2006; Betts et al., 2007; Chaplot, 2007; Felzer et al., 2009; Leuzinger and Körner, 2010), which is close to this study (Table 3).

3.2.2. Evapotranspiration (ET)

An elevated CO_2 concentration shows decreasing effects of about 2.3% and 1% on ET at the country scale under the SRES A2 and SRES B1 CO_2 scenarios, respectively (Figs. 5b, 7).

At the hydrological region scale, elevated CO_2 concentrations are projected to produce decreasing effects on ET, ranging from 0.7% to 6%, in most of the hydrological regions, especially those located in southern China (Yangtze River, Zhemin, Zhujiang, and Southwest regions) (Fig. 7).

3.2.3. Transpiration

Elevated CO_2 concentration shows decreasing effects of about 3.5% and 0.8% on transpiration at the country scale under the SRES A2 and SRES B1 CO_2 scenarios, respectively (Figs. 5c, 7). The decreasing effect is mainly spread over the southern regions, especially noticeable in the Zhemin region (Fig. 7). In contrast, elevated CO_2 is projected to exert increasing effects on transpiration in most northern regions, especially noticeable in the Inland region.

Under the no climate change scenarios, transpiration level at the national scale increases slightly with the constant CO_2 scenario and decreases slightly with both SRES A2 and SRES B1 CO_2 scenarios at the end of the 21st century (Fig. 5c3); at the hydrological region scale, the transpiration level at the end of the 21st century is projected to increase in the northern regions and be much lower than the mean level of 1950–2008 in most southern regions because of the effects of elevated CO_2 (Fig. 5c3).

3.2.4. Transpiration/Evapotranspiration (T/E)

Elevated CO_2 concentration produces slight decreasing effects under the SRES A2 CO_2 scenario and slight increasing effects under the SRES B1 CO_2 scenario on T/E at the national scale (Figs. 7, 5d).

At the hydrological region scale, increasing effects of elevated CO_2 on T/E are shown in the northern regions and in the Southwest region (Fig. 7), especially significant in the Inland region (Figs. 5d, 7). The T/E is projected to be significantly enhanced at the end of the 21st century compared to the mean level of 1950–2008 in these regions under elevated CO_2 concentration scenarios (Fig. 5d). Decreasing effects of elevated CO_2 on T/E are shown in most southern regions (Fig. 7).

As a whole, Fig. 5 indicates that elevated CO_2 concentration would produce increasing effects on runoff and decreasing effects on ET and transpiration at the national scale (Fig. 7). The increasing effects on runoff would be mainly spread over the southern regions, and the decreasing effects on ET and transpiration would be spread over the southern-most regions. Elevated CO_2 concentration is projected to produce significant increasing effects on transpiration and significant decreasing effects on runoff in the Inland region.

3.3. Evaluating the effects of climate change and CO_2 concentration enrichment on LAI

LAI, including LAI of both upper canopy (trees) and lower canopy (shrubs, grass, etc.), is used to investigate the effects of climate change and CO_2 concentration enrichment on vegetation structure variation.

Climate change is projected to produce increasing effects on lower canopy LAI at the national scale (Figs. 3a, 4) and at the most hydrological regions (Fig. 4). The increasing effects of climate change on the lower canopy were especially noticeable in the Southwest and Inland regions (Fig. 7). In contrast, climate change is projected to exert decreasing effects on upper canopy LAI at the national scale (Figs. 3b, 4). The decreasing effects are significantly spread over the Southwest region (Figs. 3b, 4). Slight decreasing effects of climate change on upper canopy LAI are projected in most of southern regions while the increasing effects were shown among most northern hydrological regions (Fig. 4).

For total LAI (sum of lower canopy and upper canopy), negligible effects were projected to be due to climate change at the national scale (Figs. 3c, 4). At regional scale, noticeable decreasing effects of climate change on total LAI were projected in southern regions (Zhujiang and Southwest regions) (Fig. 4). However, climate change would exert increasing effects on total LAI under all climate change scenarios in the northern hydrological regions, especially significant in the Inland region (Figs. 3c, 4).

Under elevated CO_2 concentration scenarios with or without climate change, the lower canopy LAI, upper canopy LAI, and total LAI would be enhanced significantly at both the national and the hydrological region scale (Figs. 3a,b,c, 4).

3.4. Comparing the effects of elevated CO_2 concentrations and climate change

The results indicated that the effects of climate change are much greater than the effects of elevated CO_2 concentration at the national scale in almost all different scenarios and at the hydrological region scale for runoff, ET, transpiration, and T/E (comparing sub-chart a1, b1, c1, d1 separately between Figs. 4 and 7). For LAI, the effects of elevated CO_2 are much greater than those of climate change at the national scale and at the hydrological region scale (comparing sub-chart a2, b2 ,c2, d2 separately between Figs. 4 and 7).

Negative effects were projected for runoff, ET, transpiration, and T/E when elevated CO_2 concentration is superimposed over climate change in some regions (Figs. 7 a1, b1): for runoff in the Inland region and for ET, transpiration and T/E in most southern regions. The negative effects were also reflected at the national scale for ET and transpiration (Figs. 7 a1, b1).

Negative effects were projected for runoff and LAI in some regions when climate change is superimposed over elevated CO_2 for runoff (Figs. 4a1, b1) and for LAI (Figs. 4a2, b2). The negative effects were noticeable on upper canopy LAI at the national scale (Figs. 4a2, b2).

3.5. Comparison of future and historical runoff levels in China

Simulations forced by CGCM climate data under the SRES A2 and SRES B1 scenarios showed climate change would have a increasing effect on runoff compared to the mean runoff level of 1950–2008 at the national scale and in most hydrological regions, especially in northern China. The Zhemin and Zhujiang regions would be the exceptions, with a depressed runoff at the end of this century compared to the historical level in these two regions (Fig. 2a). Although there is a slight increase for runoff under B1 and DCO_2 (B1) situation at the end of the 21st century while comparing to the historical levels in the Zhujiang region (Fig. 2a2), the contributing factor is the positive effects of CO_2 concentrations (Fig. 5a2).

Under the no climate change scenarios, runoff would be slightly higher at the end of the 21st century than the historical level at the country scale and in southern China (Fig. 5a3). The increasing trend would be strengthened with elevated CO_2 concentrations (Fig. 5a3). Runoff would be lower at the end of the 21st century than the historical level in most northern regions, especially in the Inland region (Fig. 5a3), and the rising CO_2 concentrations would aggravate the situation.

4. Discussion

4.1. Climate change is projected to have increasing effects on runoff at the national scale and most regions

At the national scale, considering the factor of climate change, transpiration is projected to be enhanced mainly due to the increasing effects of climate change on lower canopy LAI (Fig. 4). As a result, ET would be enhanced under climate change condition because of the increasing effects of climate change on transpiration and the increase of evaporation due to the rising temperature. At the same time, T/E would be enhanced, indicating that the increasing effects of climate change on transpiration will be stronger than on evaporation. Although the ET level is promoted, climate change is projected to exert increasing effects on runoff due to the increasing precipitation under scenarios SRES A2 and SRES B1.

In northern hydrological regions of China, climate change is projected to have increasing effects on runoff as well as ET, transpiration, T/E, and LAI (Fig. 4). In these regions, the patterns of runoff under climate change with or without elevated CO_2 concentrations are similar to the patterns of precipitation under the SRES A2 and SRES B1 scenarios. This indicates that precipitation in northern regions of China at the end of the 21st century could satisfy the water consumption of evapotranspiration, even though climate change is projected to enhance transpiration due to its increasing effects on LAI and evaporation due to the rising temperature. The most significant impact of climate change on runoff and LAI in the Inland region implies that water resources would be improved and plant growth would be promoted under the SRES A2 and SRES B1 climate scenarios in this region at the end of the 21st century.

The situation will be somewhat different in the southern regions. In the Yangtze River and Southwest regions, precipitation is projected to meet the requirement of enhanced ET and increase runoff at the same time. The transpiration proportion of ET would be enhanced partially due to the increasing effects of climate change on the lower canopy LAI in these two regions. However, climate change is projected to reduce runoff in both Zhemin and Zhujiang regions, mainly because of a small increase in precipitation with a considerable increase in ET under climate change conditions. The transpiration and the transpiration proportion of ET (T/E) would be enhanced even though the LAI would be decreased by climate change in these two regions. The major reason is that in the southern regions, transpiration would increase with the rising temperatures, keeping the canopy cool and protecting plants under even higher temperature conditions induced by the projected future climate change (Field et al., 1995).

4.2. Elevated CO_2 concentrations are projected to have increasing effects on runoff at the national scale and in most hydrological regions in China

Previous studies pointed out that elevated CO_2 concentration would leave more water at the land surface and thus increase runoff because transpiration and ET would be depressed, which is a consequence of the physiological forcing effect, the closure of stomatal conductance in relatively high CO_2 concentration situations (Field et al., 1995; Sellers, 1996; Betts et al., 2007). In this study, the physiological forcing effect depends on different hydrological regions and different climate conditions.

At the national scale in China, and in the central southern China areas, the elevated CO_2 concentrations under the SRES A2 and SRES B1 scenarios would enhance runoff due to the negative contribution to transpiration and ET as a consequence of physiological forcing effects, which is consistent with previous studies (Field et al., 1995; Sellers, 1996; Betts et al., 2007).

However, for example, in the Heilongjiang region, runoff would be enhanced whereas transpiration is also projected to be enhanced under elevated CO_2 concentration conditions (Fig. 7). In this region, elevated CO_2 concentration would reduce the stomatal conductance and thus decrease transpiration due to physiological forcing effects; on the other hand, elevated CO_2 concentration also would improve the LAI level. The improved LAI would compensate and even exceed the negative effects of stomatal closure on transpiration in this region, which indicates that one of the reasons for the decreasing effects of elevated CO_2 concentration on ET is a reduction of evaporation from the soil surface because of increasing LAI (Hungate, 2002). This pattern is also partially reflected in the Liaohe, Haihe, Yellow River, and Southwest regions. Nevertheless, the corresponding patterns of runoff, ET, and transpiration are not as consistent under different scenarios for each region as they are in the Heilongjiang region. This implies that the response of runoff to elevated CO_2 concentration also depends on the vegetation types, climate conditions, and geographical background conditions.

On the contrary, in the Inland region, elevated CO_2 concentrations would have noticeable decreasing effects on runoff due to the increasing effects on ET. The level of transpiration and T/E are projected to improve, which is one of the consequences of increasing LAI caused by rising CO_2 concentrations especially for the lower canopy. Grassland is the main land cover type in the Inland area. Improving transpiration due to the increasing LAI level of grassland is one of the major reasons for the projected decreasing effects of elevated CO_2 concentration on runoff even where stomatal closure effects exist. Reduced leaf-level transpiration can be outweighed by the increased transpiration that results from enhanced vegetation cover in semiarid areas (Leipprand and Gerten, 2006). Kergoat (2002) demonstrated that in middle to high latitudes, photosynthetic stimulation may counteract the stomatal effect and greater water losses because enhanced plant productivity may compensate the evapotranspiration decrease caused by increased CO_2 concentration. Moreover, Field et al. (1995) suggested that ET is more sensitive to changes in stomatal conductance in aerodynamically rough than in aerodynamically smooth canopies, and water savings in aerodynamically smooth ecosystems would be substantially smaller. Under the climate change conditions, although precipitation is projected to increase at the end of the 21st century in this region, more evaporation is expected by the rising temperature due to climate change in this arid area.

Other reasons could be referenced from previous studies for the pattern shown in the Inland region. Plant canopy temperature would be enhanced because of stomatal closure caused by physiological forcing effects; then the vapor pressure deficit between the plant canopy and the surrounding atmosphere will increase transpiration (Huntington, 2008). As canopy temperature increases, the driving force for transpiration increases because plants need increased stomatal opening for evaporative cooling (Field et al., 1995; Leakey et al., 2009), which will offset some of the physiological forcing effects (Huntington, 2008). The decreasing effects of elevated CO_2 concentration on runoff were also suggested by Piao et al. (2007), pointing out that the decreasing effects of vegetation structure would be more significant than the physiological forcing effects.

4.3. LAI compensation effect on runoff is not always significant

The effects of elevated CO_2 concentrations on runoff are mainly achieved in two ways: reducing transpiration per unit of leaf area and increasing productivity per unit of leaf area (Norby et al., 2005; Piao et al., 2007). First, rising CO_2 concentration levels will decrease stomatal conductance and reduce the transpiration level, which would cause a positive contribution to runoff. Second, elevated CO_2 enhances LAI and improves transpiration, which would cause a negative contribution to runoff. The elevated CO_2 concentration will set an upward or downward trend in runoff depending on which of the two aspects dominates.

Increased LAI can increase canopy conductance and potentially offset stomatal closure (Betts et al., 2007). In this study, the positive effects of enhanced LAI on transpiration would compensate for and exceed the negative effects of stomatal closure, a pattern mainly present in the Inland region, which is the most arid region in China. However, in southern moist regions, LAI is projected to increase while ET is reduced, which indicates that the stomatal closure will be the dominant factor. Gerten et al. (2008) suggested that rising CO_2 would decrease river discharge in some drylands with higher transpiration because of expanding vegetation and that rising CO_2 would increase river discharge in parts of the Northern Hemisphere with reduced transpiration because of the dominance of physiological forcing effects. Leipprand and Gerten (2006) suggested that regional differences in net effects are mainly due to the balance between the structural and physiological vegetation responses to CO_2 concentrations. In this point of view, ET tends to increase due to an expansion of vegetation and canopy size in dry areas, while the physiological effect of CO_2 concentrations on ET dominates and leads to reduced water use in wet regions (Leipprand and Gerten, 2006).

4.4. Effects of climate change is much greater than elevated CO_2 concentration

By replicating a continental runoff dataset, Gedney et al. (2006) suggested that climate change alone is insufficient to explain the increasing runoff trends in the 20th century, and suppression of plant transpiration by stomatal closure induced by CO_2 is to a large extent responsible for the continental runoff increases. In this study, under a few conditions, the runoff trend at the end of the 21st century would be changed to the opposite direction because of the effects of rising CO_2 concentrations, which implies the physiological forcing effects would be the dominant factor.

Nevertheless, our results indicate the effects of climate change on runoff would be much greater than those of by physiological forcing effects induced by CO_2 in most regions and under most scenarios. The patterns of the increasing rate of runoff in different regions are highly consistent with the corresponding patterns of precipitation. Climate change would be the dominant factor for the state of water resources in China at the end of the 21st century. Process-based simulations of global runoff using a terrestrial biosphere model (Piao et al., 2007) suggest that the observed significant increase in global runoff in the 20th century is mainly a consequence of climate change and widespread deforestation, and that the impact of climate change through radiative forcing as well as structural vegetation dynamics is stronger than that of the CO_2 physiological effects. Leuzinger and Körner (2010) argue that increased runoff due to CO_2 physiological effects would be relatively small at a landscape scale. Previous studies based on observed data or model-simulated results suggest that climate change will be the major factor that influences the dynamics pattern of runoff, especially the pattern of precipitation (Falloon and Betts, 2006; Chaplot, 2007; Alo and Wang, 2008; Gerten et al., 2008; Luo et al., 2008; Felzer et al., 2009; Leuzinger and Körner, 2010).

Although the physiological effects on runoff are relatively small, increasing CO_2 concentration may be one of the most important modifiers of the water cycle and may become more conspicuous (Robock and Li, 2006). Results under combined scenarios (climate change and elevated CO_2 concentrations) show that elevated CO_2 concentrations would strengthen the increasing effects of climate change on runoff at the national scale and in most hydrological regions.

4.5. Future runoff level in China

Our results show that water resources would be improved in northern China and depressed in southern China because of climate change (under SRES A2 and SRES B1 scenarios), and it would be nearly the opposite if no climate change is considered. Although climate scenarios consistently project higher global precipitation in the future resulting in increased runoff, the subtropical zone is projected to receive less precipitation, which depresses the runoff level (IPCC, 2007; Kundzewicz et al., 2007). In addition, runoff would decrease particularly in subtropical regions mainly due to concurrent changes in plant transpiration under hypothetical elevated atmospheric CO_2 concentrations (Gerten et al., 2004).

4.6. Limitation and future works

Although the DGVM coupled ecological and hydrological processes can demonstrate the responses of the ecosystem to climate change and elevated CO_2 concentrations at regional to global scales, the modeling uncertainties should be considered. Since future projections of precipitation by IPCC climate models are highly uncertain, there is a major scientific challenge to reconcile the observed temperature and precipitation trends with future projections (Piao et al., 2010). The simulation of CO_2 effects on photosynthesis and stomatal conductance is uncertain (Alo and Wang, 2008), and the scaling of leaf-level experiments to the canopy and ecosystem scale remains challenging (Luo et al., 2004; Norby and Luo, 2004). Moreover, different models need to be used rather than one to evaluate variation and uncertainty because of differences of model structure and parameters (Prudhomme and Davies, 2009). In future work, entropy concept can be used for uncertainty measurement and model-data fusion will be an effective method to acknowledge sources of uncertainty (Peng et al., 2011). Due to the complexity of carbon and water cycling processes, various factors should be considered in studying the dynamic trends of hydrological parameters, such as land use land cover change (Piao et al., 2007), land use and irrigation (Gerten et al., 2008), agricultural practices (Raymond et al., 2008), nitrogen limitation and ozone damage (Felzer et al., 2009; Liu et al., 2010), and tropospheric air pollution (Robock and Li, 2006).

Feedback of ecosystems to climate change and elevated CO_2 concentration is another key factor that should be considered (Quillet et al., 2010). For instance, LAI and vegetation type can change the land surface properties (e.g., albedo, aerodynamic roughness), which can then affect climate (Betts et al., 2007). Reduced transpiration would tend to decrease atmospheric moisture, potentially inducing a positive feedback to increased temperature and reduced soil moisture (Gerten et al., 2007).

5. Conclusion

The IBIS model was used to investigate the effects of climate change, elevated CO_2 concentrations, and vegetation structure on hydrological processes of China at the end of the 21st century. Our study suggests that: 1) projected climate change would have increasing effects on runoff, ET, transpiration, and T/E at the national scale and at the hydrological region scale except for runoff in southernmost regions; 2) elevated CO_2 concentrations would increase runoff at the national scale while the patterns are depend on vegetation types, climate conditions, and geographical conditions at the hydrological region scale; 3) LAI compensation effect and stomatal closure effect would be the dominant factors on runoff in the arid Inland region and southern moist hydrological regions, respectively; 4) effect of climate change is much larger than that of elevated CO_2 concentrations while increasing CO_2 concentrations may be one of the most important modifiers of water cycle; 5) water resources are projected to improve in northern China and reduce in southern China under SRES A2 and SRES B1 climate change scenarios. These results could provide scientifically sound information to public decision makers and water managers, especially for their future water resource planning and management.

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