Impacts of climate change and land use on China's water cycle: an ecosystem model-based assessment of regional differences

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Abstract Climate change and land use altered the global and regional water cycles. On the ecosystem point of view water cycle can be used to better understanding the interactions among ecosystem, climate change and land use, and hence to better manage the water resources and to make the land use policy optimal. A Dynamic Global Vegetation Model (LPJ) is used to simulate the historical water budget of Chinese ecosystems from 1901-2002 driven by changed climates, increased CO_2 concentration and land use change. Preliminary results showed that, the annual runoff and actual evapotranspiration of 102-year averages in the country level gradually increase from the northwest to southeast, reflecting the ecosystem-based feature of water resources in China (higher in forests, medium in grasslands and lower in deserts). Climate change, climate inter-annual variability and enhanced CO_2 had the potential to modify vegetation compositions and spatial distributions, thus significantly influenced the long-term water cycles in the country. Runoff increased about 734 billion m^3 from the first to second half of the last century, while the actual evapotranspiration remains relatively the same over time. Land use and land cover changes modified the potential water resources of China, positively or negatively depending on regions and time periods. Since 1990 land use reduced the actual evapotranspiration and increased the runoff. However great regional differences and temporal fluctuations of runoff occurred in the study area. More effectively managing water resource is an optimal way to mitigate climate change and to reduce water's vulnerability in China.

Keywords: actual evapotranspiration, climate change, land use, LPJ-DGVM, runoff, vegetation

1. Introduction

Changes in climate, compositions of greenhouse gases (GHGs) and land use have influenced the world's environments (IPCC, 2007). Global and regional water cycles have consequently been altered by environmental change and human disturbances (Kundzewicz et al., 2007). All regions in the world showed an overall net negative impact (high confidence) of climate change on water resources and freshwater ecosystems. Areas in which runoff is projected to decline are likely to face a reduction in the value of the services provided by water resources. The beneficial impacts of increased annual runoff in other areas will be tempered by the negative effects of increased precipitation variability and seasonal runoff shifts on water supply, water quality, and flood risks (Kundzewicz et al., 2007). As water is fundamentally important for all forms of life and is needed in almost all human activities, the impacts of climate change on water resources and their integrated management and sustainable utilization are still needed to do more comprehensive studies at regional and global scales (Oki and Kanae, 2006), especially in an anthropogenic epoch.

However anthropogenic climate change is only one of many pressures on water systems. Emissions of GHGs such as CO_2 and human activities through land use, population change, life style, economy, and food demand are other key pressures (Oki, 2005). Climate, CO_2 concentration, land use and water systems are interconnected in complex ways. Ecosystems, interacted with atmosphere and biosphere, play a key role in such interconnection and in the global water balance (Gerten et al., 2004, 2005). Through ecosystems we could better understand the water cycle in different scales and its interactions with ecosystem, climate change, CO_2 concentration and land use, and hence better manage the water resources. Such studies have recently been highlighted at regional and watershed scales.

China has a vast area with various climate regimes, diverse ecosystems, and long-term land use history. Climate changes associated with strong human disturbances have the potential impacts on Chinese ecosystems (Ni, 2009 in press). Swelling population, rapid development of economy, increasing urbanization, and alternation of land use regime stretched land and water resources of the country, and hence will influence the food security. China has been facing increasingly severe water scarcity characterized by insufficient local water resources as well as reduced water quality due to three reasons: uneven spatial distribution of water resources; rapid economic development and urbanization with a large and growing population; and poor water resource management (Jiang, 2009). The assessment of the impacts of climate change and land use on water cycle is important and necessary to evaluate China’s water vulnerability and to improve water resource management of the country (Ying, 2000). Such tasks of water resource assessment and management will contribute greatly to China’s food security, economic development and life quality. In this paper the impacts of climate change, CO_2 concentration and land use on water cycles are simulated by a dynamic vegetation model that coupled water and carbon cycles in ecosystems. Regional differences of these impacts are then evaluated in order to better manage the water resources in various rivers and watersheds of China.

2. Data and methods

2.1 The LPJ model

The Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM: Sitch et al., 2003) combines ecophysiological and ecological treatments of terrestrial vegetation dynamics, carbon and water cycling in a modular framework. The model includes the linkages and feedbacks between photosynthesis and plant water balance through canopy conductance, and the close coupling between these fast processes and representations of slower ecosystem-level processes including vegetation resource competition and production, tissue turnover, growth, establishment and mortality, soil and litter carbon turnover and the fire regime. Vegetation structure and competition are represented by nine plant functional types (PFTs) differentiated by phenology, physiology, physiognomy, disturbance-response attributes and bioclimatic constraints (Sitch et al., 2003). The model simulates the coupled terrestrial carbon and water cycles, thus it is well suitable for investigating biosphere–hydrosphere interactions over large domains. The hydrological processes of the LPJ were then improved (Gerten et al., 2004), and global water balance was evaluated using the modified model (Gerten et al., 2005). The most important changes included additional processes such as interception and soil evaporation, and the stochastic distribution of precipitation. Actual and potential evapotranspiration, soil water storage and runoff were then successfully predicted, showing a well agreement with observations and results from state-of-the-art global hydrological models (Gerten et al., 2004).

2.2 The input data

The LPJ hydrological version was run at a grid resolution of 10′ by 10′ and driven by monthly values of temperature, precipitation, cloudiness and wet days, as well as soil texture and atmospheric CO_2 concentration. Land use data are an addition driver.

The modern climatology of China was extracted from the high-resolution gridded dataset of CRU TS 2.1 (Climate Research Unit, University of East Anglia, UK). This global data set provides monthly observations of nine climate variables from meteorological stations between January 1901 and December 2002 on a 0.5° by 0.5° grid over the land surface (Mitchell and Jones, 2005). The data were interpolated into 10′ resolution using the thin plate smoothing spline surface fitting technique (Hutchinson, 2006, ANUSPLIN version 4.36) and the STRM digital elevation model (Farr et al., 2007). A data set of historical global atmospheric CO_2 concentrations was derived from a combination of ice-core measurements and atmospheric observations (Sitch et al., 2003) and was extended through to 2002 using the averaged atmospheric observations at Mauna Loa and the South Pole. To obtain a more accurate atmospheric CO_2 concentration of China, the global CO_2 records were linearly calibrated using recent observations of three sites (http://cdiac.ornl.gov/trends/co2/cmdl-flask/) in western China (Waliguan Mt.), Mongolia (Ulaan Uul), and Korea (Tae-Ahn Peninsula). The soil texture dataset was taken from the Soil Texture Map of Chinn that has been used in Chinese vegetation modelling (Ni et al., 2000). The historical land use of the HYDE 2.0 was used to simulate the impact of land use on water cycle. The dataset includes the distribution of cropland, pasture, and potential natural vegetation and is on a 0.5° grid for 1700–2000 (Klein Goldewijk, 2001). The land use only occurred in 1900, 1950, 1970 and 1990 at 10′ resolution was extracted from the global dataset using GIS.

2.3 Analytical framework

The study only focused on the water cycle in China from 1901-2002 rather than the carbon and biome changes. The runoff and actual evapotranspiration (AET) were mainly analyzed in the entire country and in different regions representing various river systems and watersheds (Table 1).

Table 1: Division of regions representing various river systems and watersheds

Region	Locations	Watershed
northeastern China	>42° N, >120° E	Heilongjiang and Songliao Rivers
eastern China	33-42° N, >112° E	Huang Huai Hai Rivers

northern central China	34-42° N, 107-112° E 34-37° N, 100-107° E	Yellow River
southern central China	26-34° N, 95-117° E	Yangtz River
southeastern China	23-33° N, >117° E	Southeast coast incl. Taiwan Island
southern China	<26° N, <117° E	Pearl River and south coast incl. Hainan Island
northern China	>42° N, 107-120° E >38° N, 95-117° E	Inner Mongolia and Hexi Corridor rivers
western China	>38° N, 90-95° E / >36° N, <90° E	Junngar and Tarim rivers
Tibetan Plateau	<38° N, 90-95° E / <36° N, <90° E	alpine rivers

3. Results

3.1 Water fluxes under changed climate and enhanced CO_2

Annual runoff and AET of 102-year averages in the country showed gradually increase trend from the northwest to southeast, reflecting the ecosystem-based feature of water fluxes in China (Fig. 1a, b). That is to say, high evapotranspiration (Fig. 1a) and runoff (Fig. 1b) occurred in forests, intermediate in grasslands and low in deserts, associated with the similar pattern of mean annual precipitation. Climate change, its inter-annual variability and increased CO_2 concentration had the potential to modify vegetation composition and spatial distribution (data not shown), thus significantly influenced the long-term water cycles in the country. Averaged annual mean AET fluctuated (with a slight increase) before 1930, increased during 1930-1950, then gradually decreased from 1950-1980, and finally increased since 1980 to 2002. However the range of annual AET is basically between 250-275 mm/year and didn't show significant change (Fig. 2a). The runoff showed the similar trends of change during the last century, but the range of fluctuation is much stronger than that of evapotranspiration and showed a significant increase (Fig. 2a). Such changes resulted in a 734 billion m^3 increase of annual runoff from the first (181.24×10^{10} m^3 per year) to the second half (189.48×10^{10} m^3 per year) of the last century, while the annual AET reduced very slightly from 258.37 to 257.16×10^{10} m^3 per year (Fig. 2b).

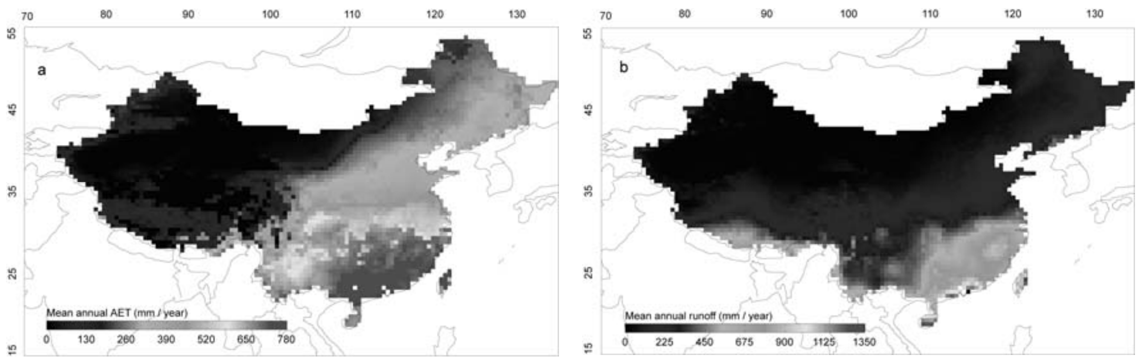

Figure 1. Spatial patterns of water fluxes in China: (a) annual mean actual evapotranspiration and (b) annual mean runoff. Data were averaged over the past 102 years from 1901 to 2002.

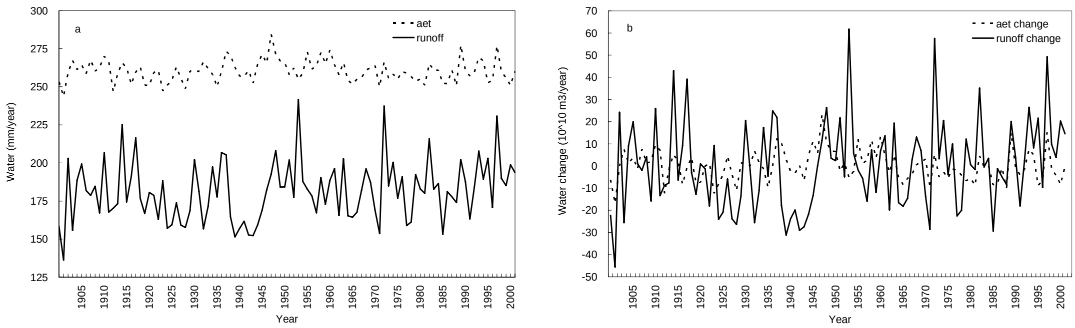

Figure 2. Dynamic changes of water fluxes in China during 1901-2002: (a) mean actual evapotranspiration and runoff, and (b) total actual evapotranspiration and runoff. Mean flux data were averaged over the country. Total flux data were summarized over the country and calculated the difference to the 102-year average.

However both AET and runoff in China had great regional differences, implying the variations of different river systems and big watersheds as well as different vegetation distributions (Fig. 3a, b). Southern China (mainly the Pearl River watershed) and southeastern China had the higher evapotranspiration (600-750 mm/year, Fig. 3a) and also the runoff (400-900 mm/year, Fig. 3b). Southern central China, eastern China, northeastern China and northern central China had the medium evapotranspiration (200-500 mm/year, Fig. 3a), while only the southern central China and Tibetan Plateau had the intermediate runoff (200-400 mm/year, Fig. 3b). The Tibetan Plateau, northern China and western China had the lowest evapotranspiration (<100 mm/year, Fig. 3a), while the eastern China, northeastern China, northern central China, northern China and western China had the lowest runoff (<200 mm/year, Fig. 3b). The AET had less temporal fluctuations (Fig. 3a), but runoff had very strong fluctuations over time especially in watersheds in southern part of China where has higher values of runoff (Fig. 3b), indicating the high temporal variability of rainfall and river discharge in this area.

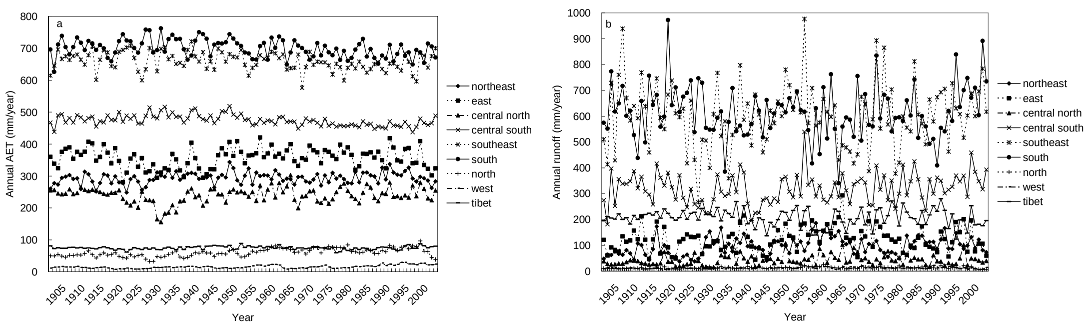

Figure 3. Dynamic changes of water fluxes in different rivers and watersheds during 1901-2002: (a) mean actual evapotranspiration and (b) mean runoff. Data were averaged over the regions.

3.2 Impact of land use on water fluxes

Land use and land cover changes modified the potential water resources of China, positively or negatively depending on regions and time periods, especially in the highly human-disturbed eastern China. The overall trend was water reduction. Since 1990 land use and land cover changes (mainly agricultural activities) obviously reduced the AET of 6.27 million m^3 per year and increased the runoff of 3.02 million m^3 per year (Fig. 4).

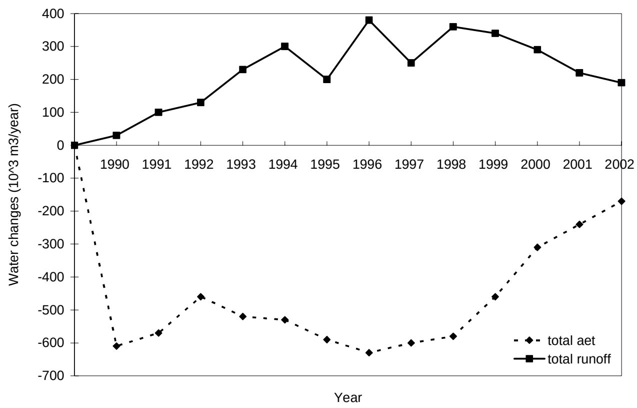

Figure 4. Land use altered water fluxes in China since 1990.

4. Discussion

This is a very preliminary study about the impacts of climate change and land use on China's water fluxes, using global climate and land use datasets and a global dynamic vegetation model. The application of global vegetation model to regional scale of China was successful, but also had problems in vegetation classification and parameterization (e.g. Ni et al., 2000; Ni, 2009 in press). The global climate dataset basically characterized the world's climate features, but failed in far remote areas where have very sparse meteorological stations such as in the high latitudes and mountains (Mitchell and Jones, 2005). The climate data of northwestern China and Tibetan Plateau derived from the CRU global dataset have obviously bias due to the lack of weather stations in temperate and alpine deserts and sparse stations in the non-settlement regions. This might affect the spatial interpolation of data. Such bias could lead to over- or underestimate of water fluxes.

On the other hand, the global land use dataset (Klein Goldewijk, 2001) has very coarse spatial resolution (0.5 degree) and also has very coarse temporal resolution (50-year interval before 1950 and 20-year interval during 1950-1990). The data only include pasture and cropland and have no information about afforestation and deforestation. However vegetation restoration and forestation could reduce the potential water yield in headwater watersheds of China, especially in the semi-arid Loess Plateau (Sun et al., 2006). These disadvantages greatly influenced the accuracy of water flux prediction in China, especially in the eastern, southern and northern parts of China where had long-term forestry activities and convention of forest to pasture and cropland. Therefore both more accurate climate and land use data from China's observation and investigation are further needed in order to more preciously simulate the water conditions.

This vegetation model-based simulation revealed that climate change and CO_2 enrichment enhanced runoff of Chinese ecosystems in the recent half century, and land use change reduced evapotranspiration and also enhanced runoff in some regions in the end of 20th century. However, the study didn't take some important points of water use into account, for example, the groundwater exploitation, water transfer, consumptions from agriculture, industry and urban population, which all have uncertainties on water cycle estimates and might reduce greatly the runoff (e.g. Fu et al., 2004). Such conditions have significant regional variations. Associated changes of climate and land use also have strong spatial differences. So the impacts of these factors on China's water resources are location- or basin-dependent, positively or negatively (e.g. Ying, 2000; Kirshen et al., 2005), but in the country level the water shortage will happen in the future (Ying, 2000). The present study only provided a simple clue of water changes in the point of ecosystem view.

The impacts of climate change and land use on water cycles are nearly impossible to adjust; improving water resource management is therefore a more effective (and more optimal) option that can mitigate China's vulnerability to water shortage (Jiang, 2009). However, improving water resource management is a long-term task requiring a holistic approach with constant effort (Jiang, 2009) in order to meet the sustainable development of water in the future under both climate and land use changes. Different regions of the country must have various strategies planned and implemented by both the central government and by local governments.

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