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# Coupled modeling of land hydrology−regional climate including human carbon emission and water exploitation

XIE Zheng-Hui [a,*], ZENG Yu-Jin [a,b], XIA Jun [c], QIN Pei-Hua [a], JIA Bing-Hao [a], ZOU Jing [d], LIU Shuang [a,b]

[a] State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

[b] College of Earth Science, University of Chinese Academy of Sciences, Beijing 100049, China

[c] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China

[d] Institute of Oceanographic Instrumentation, Shandong Academy of Sciences, Qingdao 266001, China

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## Abstract

Carbon emissions and water use are two major kinds of human activities. To reveal whether these two activities can modify the hydrological cycle and climate system in China, we conducted two sets of numerical experiments using regional climate model RegCM4. In the first experiment used to study the climatic responses to human carbon emissions, the model were configured over entire China because the impacts of carbon emissions can be detected across the whole country. Results from the first experiment revealed that near-surface air temperature may significantly increase from 2007 to 2059 at a rate exceeding 0.1 °C per decade in most areas across the country; southwestern and southeastern China also showed increasing trends in summer precipitation, with rates exceeding 10 mm per decade over the same period. In summer, only northern China showed an increasing trend of evapotranspiration, with increase rates ranging from 1 to 5 mm per decade; in winter, increase rates ranging from 1 to 5 mm per decade were observed in most regions. These effects are believed to be caused by global warming from human carbon emissions. In the second experiment used to study the effects of human water use, the model were configured over a limited region—Haihe River Basin in the northern China, because compared with the human carbon emissions, the effects of human water use are much more local and regional, and the Haihe River Basin is the most typical region in China that suffers from both intensive human groundwater exploitation and surface water diversion. We incorporated a scheme of human water regulation into RegCM4 and conducted the second experiment. Model outputs showed that the groundwater table severely declined by ~10 m in 1971−2000 through human groundwater over-exploitation in the basin; in fact, current conditions are so extreme that even reducing the pumping rate by half cannot eliminate the groundwater depletion cones observed in the area. Other hydrological and climatic elements, such as soil moisture, runoff generation, air humidity, precipitation, wind field, and soil and air temperature, were also significantly affected by anthropogenic water withdrawal and consumption, although these effects could be mitigated by reducing the amount of water drawn for extraction and application.

*Keywords:* China; Hydrological cycle; Climate change; Anthropogenic activities; Land−atmosphere coupling modeling

## 1. Introduction

Climate change has become a focus of global attention (Parmesan and Yohe, 2003; Dufresne et al., 2013), and the land hydrological cycle, which connects the lithosphere, biosphere, and atmosphere, is a key issue in research on climate change (Lorenz and Kunstmann, 2012; Wu et al., 2013). The

* Corresponding author.
*E-mail address:* zxie@lasg.iap.ac.cn (XIE Z.-H.).

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hydrological cycle is affected by both natural and anthropogenic processes, and its feedback could negatively impact land eco-hydrological systems, the distribution of water resources, environmental changes, and the climate at local, regional, or even global scale (Xie et al., 2014; Zeng et al., 2016a, 2017a,b). In China, studies on the land hydrological cycle are fairly important because of the uneven distribution of water resources throughout the country (Yang et al., 2014). However, the land hydrological cycle in China, especially in its eastern monsoon region, where one-third of the country's territory is occupied by over 70% of the population, has been dramatically affected by human water extraction and application; this perturbation has impaired water security in the contexts of population expansion and economic development (Gao et al., 2008). Besides water resource insecurity, other problems, such as extreme hydrological events (e.g., droughts and floods) and ecological and environmental degradation, also dominate eastern China (Piao et al., 2010).

The relationship between land hydrological systems and climate is complex and deserves comprehensive study. Projections from the IPCC have shown significant global warming and noticeable alterations in the frequency and intensity of precipitations from 2000 to 2100 (IPCC, 2014). Changes in global climate are expected to affect the hydrological cycle and alter the availability of surface water and groundwater stored in aquifers; various other associated impacts on natural ecosystems and human activities may also be predicted (Xia, 2010). China, because of its significant heterogeneity in terms of its geographical environment, is extremely vulnerable to climate change (Piao et al., 2010). Evidence shows that the climate in China has substantially changed over the last 50 years (Cholaw et al., 2003; Shi et al., 1995; Gerlitz et al., 2014). Climate change in China also shows a considerable similarity to global change (Ding et al., 2007).

Measurements show that the average land temperature in China had increased by 0.9–1.5 °C from 1909 to 2011; this increase is higher than the average global increase of 0.74 °C (Wang et al., 2014). Although increase trends over the last 15 years have been mitigated, the country continues to suffer through the warmest period recorded in recent history. Precipitation in China has been modified by climate change. The northern and northeastern regions of China, for example, have experienced heavily decreasing trends of annual precipitation over the last 50 years, causing drought and water-food shortages in several areas (Gemmer et al., 2004). A recent Water Resources Bulletin (MWRPRC, 2015) showed that annual precipitation in the four major basins of northern China (Yellow River Basin, Huaihe River Basin, Haihe River Basin and Liaohe River Basin) decreased by 6% in 1980–2000 in comparison with 1956–1979; available water resources also decreased by 25%. The effects of the uneven distribution of water resources in China is further exacerbated by climate change (Shi et al., 1995).

Human water exploitation, such as irrigation, is also known to affect the hydrological cycle and climate. Boucher et al. (2004) estimated that water vapor flux from irrigation could reach as high as 300 kg $m^{-2}$ per year in areas where irrigation is intensive and thus promote atmospheric water conditions. Sacks et al. (2009) demonstrated that irrigation could reduce the sensible heat flux over northern mid-latitude regions (e.g., the central United States, southeast China, and portions of southern and southeast Asia), thereby cooling the global average temperature by ~0.5 °C.

The influences of human water exploitation are not restricted to land–atmosphere fluxes. Haddeland et al. (2014) pointed out that runoff generation (RG) has decreased by over 15% as a result of human consumption within some river basins in the Middle East, Central Asia, and the Indian subcontinent. In central and eastern China, where human activities are intensive, the climate can also be modified by human water application. Zou et al. (2014, 2015) noted that human groundwater exploitation in the Haihe River Basin, northern China, was particularly severe in 1965–2000. Groundwater pumping deepened the water table, modified the existing soil moisture, and caused wetting and cooling effects in the lower troposphere through agricultural irrigation and industrial and domestic use. These effects could extend outside the basin, especially in regions downwind of the prevailing westerly wind. The effects of human water regulation on climate may further redistribute water resources, causing unexpected results and preventing the sustainable use of these resources.

Interpreting interactive processes between human activities, the land hydrological cycle, and the climate; building a modeling system that represents the land hydrological cycle and land hydrology–regional climate in the eastern monsoon region of China; revealing near-air temperature (NAT), precipitation, evapotranspiration, and RG responses to natural and anthropogenic climate forcing; and analyzing the effects of human water exploitation on the hydrological and climatic system are very important in efforts to understand the hydrological cycle and climate change under a variety of human activities and internal climatic variability. It also benefits us in developments of carbon emission strategies to alleviate global warming, improvements of water management to sustain available water resources, and predicting future climate change. The nature climate forcing in this paper is defined as changes in solar constant, which is the mean solar electromagnetic radiation per unit area incident on earth and aerosol emissions from volcanic activities; the anthropogenic climate forcing is defined here as air and sea temperature increases caused by human carbon emissions; the human water exploitation is defined as the human surface water diversion, the groundwater pumping, and the agricultural, industrial, and domestic water use. These issues are also key research topics of the National Basic Research Program of China under Grant No. 2010CB428403 “Coupled modeling of the land hydrology–regional climate and analysis of the change mechanism of the hydrological cycle” and fundamental issues in hydrology and earth sciences. Overall, the research goals of this study are to quantify the hydrologic and climatic responses to human activities including both human carbon emissions and anthropogenic water use in China by conducting regional climate models. This study is meaningful in advancing our understanding over the role of human disturbances in the changing climate. The scientific problems related to this