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

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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

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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 studies include: 1) How do some key hydrologic and climatic elements respond to human activities of carbon emissions and water use in China? 2) Are these effects of carbon emissions and water use significant enough to be detected? 3) Can the impacts be mitigated by cutting off the human water withdrawal amount?

2. Climate change in China under the RCP4.5 scenario

China is vulnerable to climate change induced by increasing concentrations of atmospheric CO_2. Understanding how some key climatic (NAT, precipitation, evapotranspiration) and hydrological elements (RGs) respond to future natural and anthropogenic climate forcing is key for water resource managers and decision-makers implementing programs to adapt to and mitigate climate change and coupled human activities (Xia, 2012).

To investigate future NAT, precipitation, evapotranspiration, and RG changes under natural and anthropogenic climate forcing, we applied the technique of dynamic downscaling by nesting a high-resolution regional climate model (RCM) within a coarser resolution global climate model (GCM). The dynamic downscaling technique has been demonstrated to be a strong tool for addressing the disparity between the coarse spatial scales of GCMs and the demand of high-resolution outputs (Wilby and Wigley, 1997; Hewitson and Crane, 2006) and widely applied to many previous studies. The RCM uses the GCM to define atmospheric boundary conditions around a finite domain from which the physical and dynamics of the atmosphere are modeled using the horizontal grid spacing of the former.

2.1. Model description and experimental setup

The RCM applied in the study was RegCM-4.3.4 (hereinafter referred to as RegCM4) (Giorgi et al., 2012) from the International Center for Theoretical Physics. RegCM4 is a three-dimensional, σ-vertical coordinate, hydrostatic, compressible model with a dynamical core based on a fifth-generation mesoscale modeling system (MM5) (Grell et al., 1994) from the Pennsylvania State University/National Center for Atmospheric Research (PSU-NCAR). RegCM4 shows improved performance in several respects compared with previous versions of the model (Giorgi et al., 2012), and can accurately simulate temporal variability based on geographical regions and seasons (Oh et al., 2014). RegCM4 has been used to model regional climate in a number of previous studies (Qin et al., 2013, 2014; Zou et al., 2014; Yu et al., 2014; Qin and Xie, 2016).

In this study, outputs from the GCM GFDL-ESM2M (Griffies et al., 2011) were adopted to generate initial and boundary conditions in RegCM4. The dataset of GFDL-ESM2M was obtained from CMIP5 (Taylor et al., 2012) under the RCP4.5 scenario. RCP4.5 provides a common platform for climate models to explore climate system responses to stabilization of the anthropogenic components of

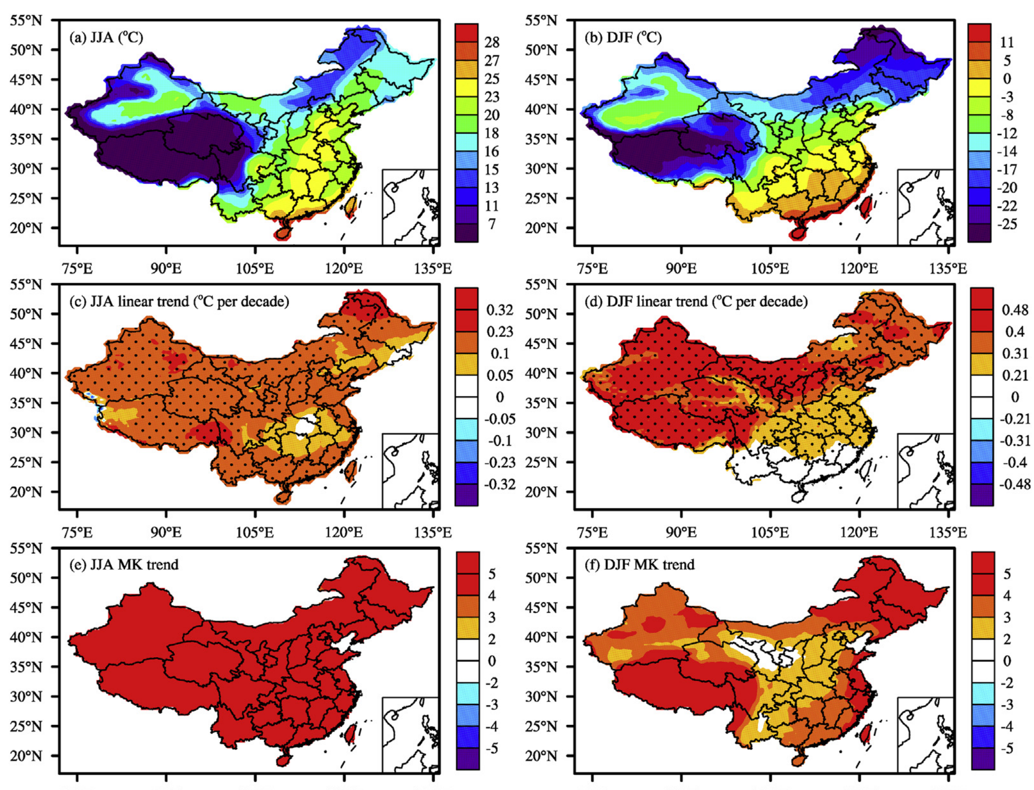

Fig. 1. Spatial patterns of (a, b) climatological near-surface air temperature, (c, d) linear trends, and (e, f) Z values of Mann−Kendall trend tests for summer (a, c, e) and winter (b, d, f) of 2007−2059. Patterns are obtained from the downscaling results of RegCM4. Stippled areas indicate regions where the regression coefficients of linear trends passed the 95% confidence level of Student's t-test.

radiative forcing, which is the focus of the present work (Thomson et al., 2011).

RegCM4 was run over East Asia including all of China and centered at (36°N, 102°E), with a horizontal resolution of 60 km, 120 (long.) × 90 (lat.) grid points, and 23 vertical layers. The model top was set to 50 hPa. The simulation results were regridded into 140 (long.) × 80 (lat.) grids with a resolution of 0.5° × 0.5° using linear distance-weight interpolation between stations and grid points (Xie et al., 2007). The results of RegCM4 were integrated for 53 years (2007–2059) under RCP4.5. To validate the model, we also conducted historical runs over the same region with RegCM4 for the period 1982–2001 using observed historical air CO_2 concentrations and initial and boundary conditions from GFDL-ESM2M. The observed daily data sets (i.e., precipitation, minimum temperature, and maximum temperature) of 753 weather meteorological stations from 1982 to 2001 provided by China Meteorological Administration were adopted for model evaluation of these runs. More information on model validation and the historical runs can be obtained from Qin and Xie (2016).

2.2. Changes in climatic elements

We first analyzed the model outputs of NAT from the RegCM4 simulation described above. Fig. 1 shows the spatial patterns of climatological NAT and its regressed linear trends for the summers and winters of 2007–2059. We also conducted Mann–Kendall trend tests (Mann, 1945) to supplement trend identification because the assumption of a Gaussian distribution for data errors in a linear regression model may be not met in China's significantly heterogeneous environments. In Fig. 1a and b, summer NAT in the eastern monsoon region of China ranges from 7 °C to 30 °C where the NAT in Hainan and Taiwan is higher than 11 °C, while winter NAT in northeastern China is as low as −17 °C. These reflect spatial patterns of north-low to south-high in both seasons. In Fig. 1c and d, most of China may be expected to suffer from a significant increase in NAT in 2007–2059. The linear trends are higher than 0.1 °C per decade in most areas, indicating the high possibility of experiencing the adverse effects of anthropogenic climate forcing even in RCP4.5. Fig. 1e and f reveals that the Mann–Kendall trend test results support the linear regression findings: most areas in China may suffer from significant temperature increases in the RCP4.5 scenario.

Fig. 2 shows the spatial patterns of climatologic precipitation and its linear trends in summer and winter of 2007–2059. Future summer precipitations are mainly distributed in southern China and could reach a maximum of 650 mm; by contrast, northern and northeastern China will receive only ~300 mm of precipitation (Fig. 2a and b). Compared with that in northwestern China, which is a fairly arid region, precipitation in eastern China is relatively richer. In winter, the magnitudes of precipitation are much lower than

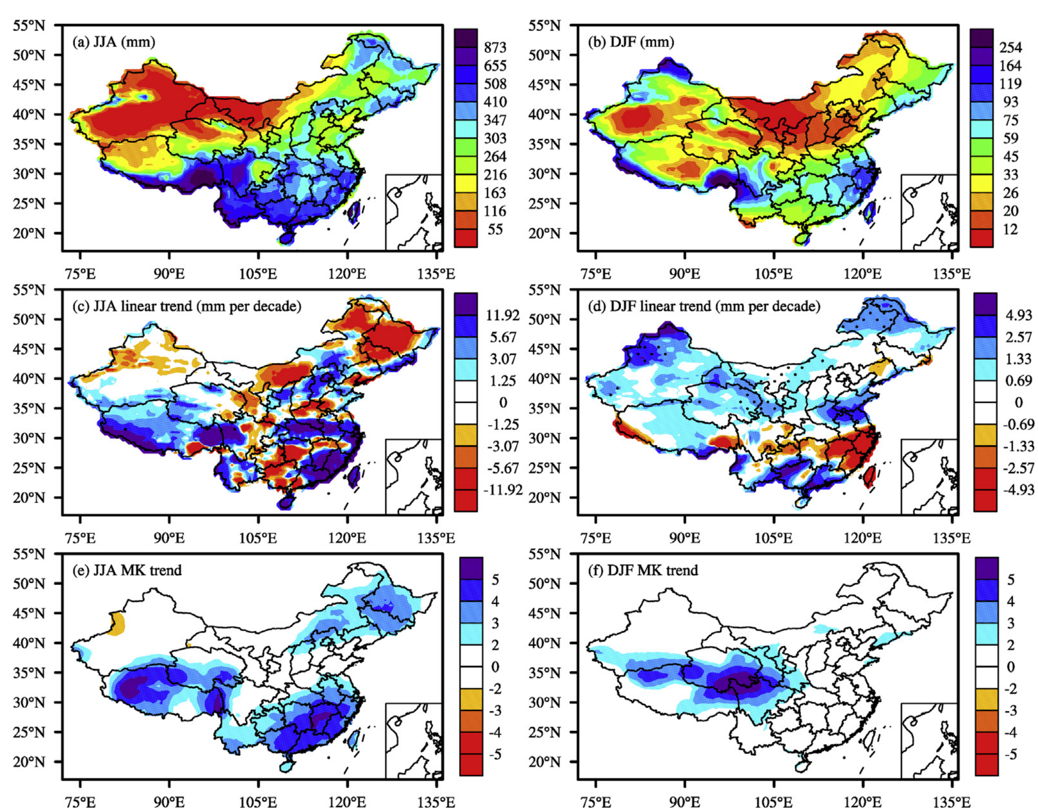

Fig. 2. Spatial patterns of (a, b) climatological precipitation, (c, d) linear trends, and (e, f) Z values of Mann–Kendall trend tests for (a, c, e) summer and (b, d, f) winter of 2007–2059. Patterns are obtained from the downscaling results of RegCM4. Stippled areas indicate regions where the regression coefficients of linear trends passed the 95% confidence level of Student's *t*-test.

those in summer; even in humid regions, winter precipitation is expected to be no more than 200 mm. Fig. 2c and d reveal increasing trends in summer precipitation in northern and southeastern China, but values fail to pass Student's t-test. In winter, large areas in northern and northeastern China show statistically significant increasing trends of precipitation. In Fig. 2e, Mann−Kendall test results indicate the possibility of an increase in summer precipitation in southwestern and southeastern China. For winter, however, Mann−Kendall predictions are markedly different from the linear regression results, indicating high uncertainty in precipitation predictions (Fig. 2f).

Fig. 3 shows the spatial patterns of climatological evapotranspiration and its linear trends in the summer and winter of 2007−2059. Future evapotranspiration patterns in China correspond to precipitation patterns identified in the summer (Fig. 3a and b). Summer evapotranspiration may be expected to exceed 260 mm in southern China and range from 200 mm to 250 mm in northern and northeastern regions of the country. Winter evapotranspiration may be expected to be rather low over the entire country because of low temperatures or a lack of precipitation. In Fig. 3c and d, a large portion of northern and northeastern China shows an increasing trend in summer evapotranspiration, and differences observed pass Student's t-test. By contrast, no similar trend is observed in southern part of the country. Predictions further reflect a slight decreasing trend in summer evapotranspiration in Hunan and Sichuan provinces, thus indicating that future evapotranspiration in southern China may be controlled by water conditions instead of changes in temperature. In winter, most regions of China show significant increasing trends in evapotranspiration. In Fig. 3e, Mann−Kendall tests of summer evapotranspiration corroborate the results of linear regression over southwestern China but do not perfectly match findings in other regions. For the winter, the tests indicate a decreasing evapotranspiration trend over southwestern China and coastal areas of eastern China, corresponding well to the linear regression results (Fig. 3f). Taken together, these findings indicate that predicted trends of future evapotranspiration in China may be more certain in winter than in summer.

RG is a key indicator of available water resources on land. Fig. 4 shows the spatial patterns of the climatological RG and its linear trends in summer and winter of 2007−2059. The Yangtze River Basin may be expected to show the highest summer RG among the areas studied; in fact, RG in most areas within this basin exceeds 300 mm (Fig. 4a, b). In other areas of the eastern monsoon region of China, RG ranges from 20 mm to 180 mm. The future winter RG is predicted to be nearly an order of magnitude lower than the summer RG. Fig. 4c and d shows generally increasing trends of summer RG in the eastern monsoon region of China, except in the North China Plain, where RG decreases in summer. However, most of the results in these regions did not pass Student's t-test, which indicates a high level of uncertainty in future RG predictions.

In winter, although the magnitudes of the linear regression coefficients of the RG trends are small, they are statistically

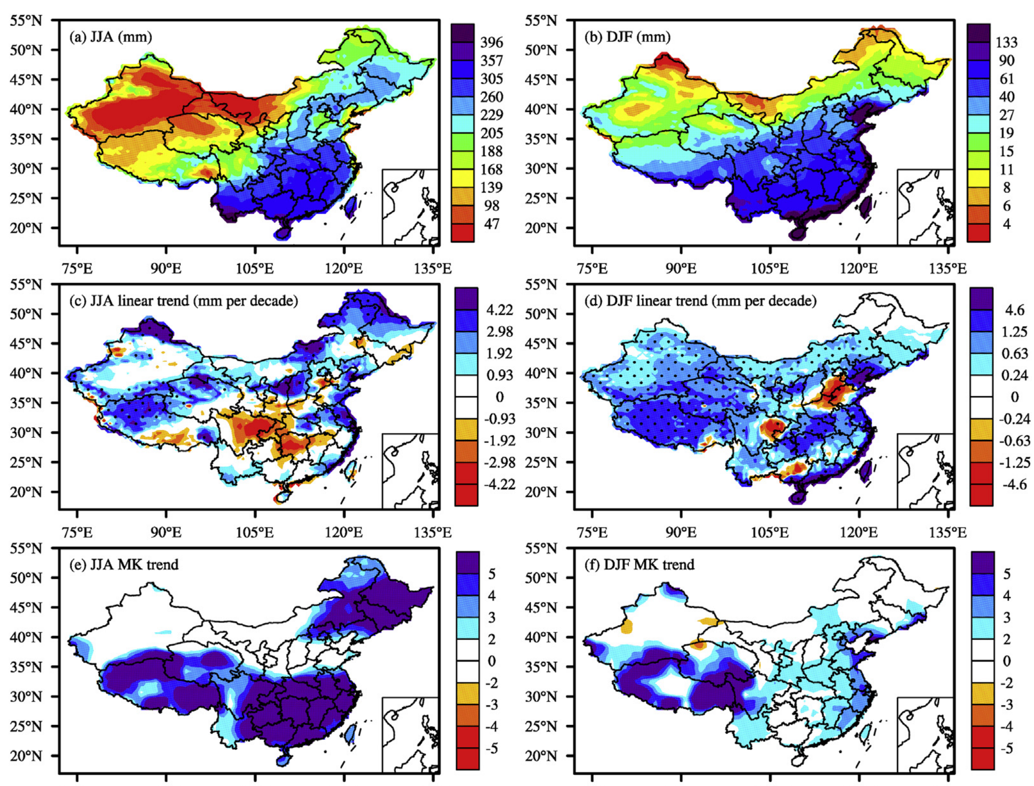

Fig. 3. Spatial patterns of (a, b) climatological evapotranspiration, (c, d) linear trends, and (e, f) Z values of Mann−Kendall trend tests for (a, c, e) summer and (b, d, f) winter of 2007−2059. Patterns are obtained from the downscaling results of RegCM4. Stippled areas indicate regions where the regression coefficients of linear trends passed the 95% confidence level of Student's t-test.

significant. In Fig. 4e, Mann–Kendall tests of summer RG corroborated the increase trends determined by linear regression over southeastern China and part of one region in northeastern China. In winter (Fig. 4f), however, few regions show the same trends in both the Mann–Kendal test and linear regression, likely because of the aforementioned high uncertainty in winter precipitation predictions.

3. Hydrological and climatic responses to human water exploitation

Besides greenhouse gas emissions, human activities, such as large-scale irrigation, groundwater exploitation, crop cultivation, water transfer project, artificial water conveyance, and land use/cover change, can also modify the hydrological cycle and climate (Xie and Yuan, 2010; Di et al., 2011; Chen and Xie, 2010; Xie et al., 2012; Zeng et al., 2016b). In the eastern monsoon region of China, groundwater exploitation in the Haihe River Basin, northern China, has become a popular research topic among hydrologists, meteorologists, geographers, geologist, and even water managers conducting studies on hydrological changes (Bao et al., 2012). Liu et al. (2001) pointed out that groundwater pumping in the basin has become extremely severe since the 1980s. In the Hebei portion of the basin alone, over-exploitation has been estimated to exceed 5 billion m^3 of groundwater per year, and the total net depletion of groundwater resources has been estimated to exceed 150 billion m^3 (Xia et al., 2014). Hebei province, which occupies only ~5% China's total land area, contributes more than a third of the total water depletion of the entire country, forming seven groundwater depletion cones with areas of over 1000 km^2. Large-scale farmland irrigation and intensive water consumption by the industry and residents have also contributed to changes in the hydrological cycle and regional climate.

To investigate the effects of anthropogenic water regulation in the Haihe River Basin on the land hydrological system and regional climate, a scheme for human water withdrawal and use was developed and incorporated into RegCM4. We then conducted several simulations using the modified RCM to reveal hydrological and climatic responses to anthropogenic water regulation in the basin.

3.1. Model development

We applied RegCM4 with the land surface module Community Land Model version 3.5 (CLM3.5) (Oleson et al., 2008) as the host model in this study and presented a scheme describing the anthropogenic water withdrawal and use in the model. As shown in Fig. 5, the stream flow and groundwater resource in each grid were exploited to meet the given human water demand per unit time and area. The total applied water resource was divided into three aspects, agricultural irrigation, industrial water use, and domestic water

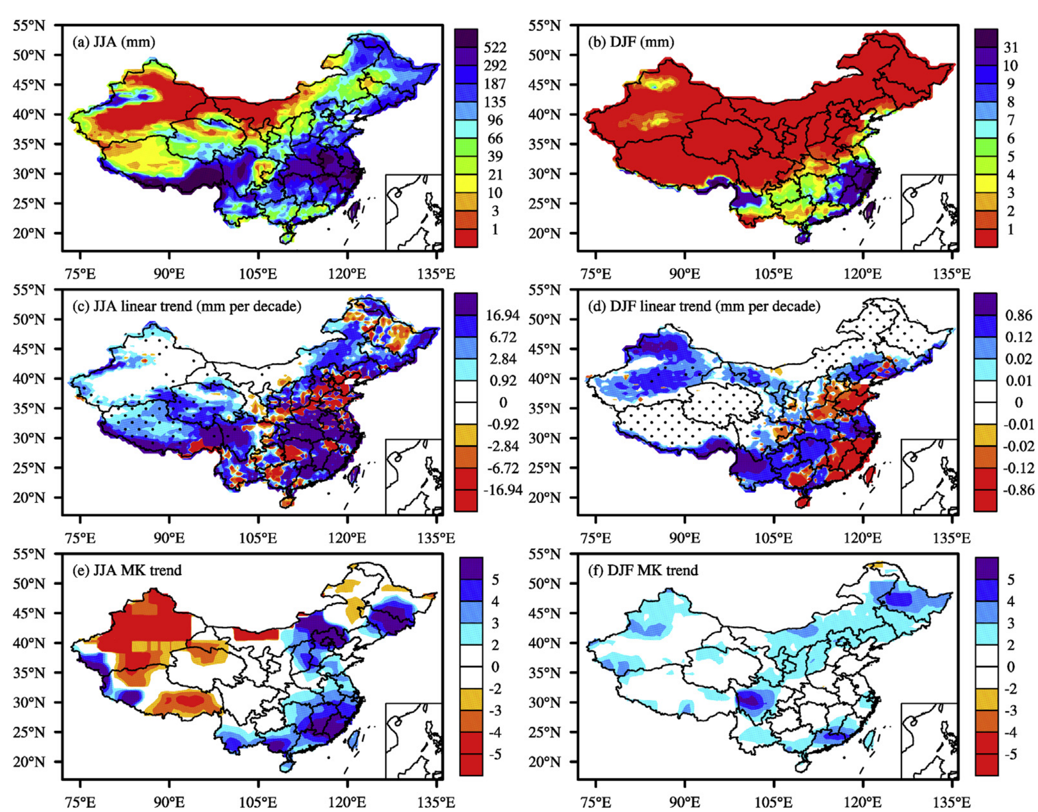

Fig. 4. Spatial patterns of (a, b) climatological runoff generation, (c, d) linear trends, and (e, f) Z values of Mann–Kendall trend tests for (a, c, e) summer and (b, d, f) winter of 2007–2059. Patterns are obtained from the downscaling results of RegCM4. Stippled areas indicate regions where the regression coefficients of linear trends passed the 95% confidence level of Student's t-test.

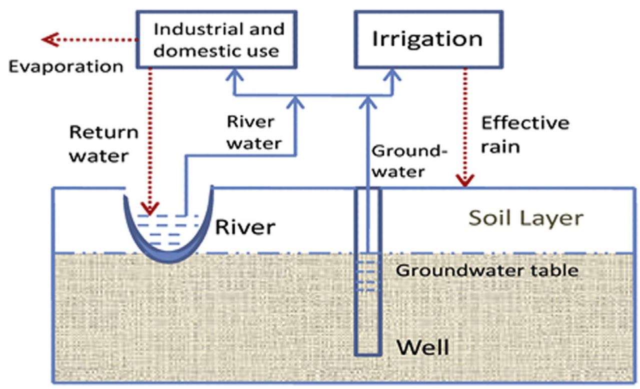

Fig. 5. Framework of simulated human-induced water resource exploitation and application processes.

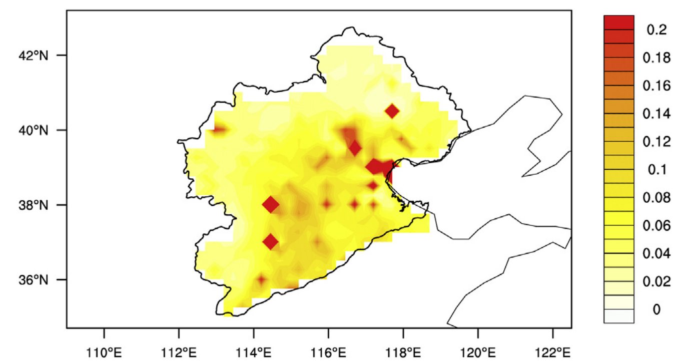

Fig. 6. Spatial pattern of the estimated total water demand (m) in the year of 2000 over the Haihe River Bain, northern China.

use. The water used for irrigation was applied directly to the ground surface, bypassing the canopy, and the water applied for industrial and domestic purposes was treated as two sinks: the net water consumption was treated as evapotranspiration and discharged to the atmosphere and the rest was assigned to wastewater and discharged to stream channels. This scheme was then incorporated into CLM3.5.

3.2. Estimating water supply and demand in the Haihe River Basin

The annual water demand in each grid cell was estimated according to the data of irrigation rate, irrigated area, water use per capita, population, gross domestic product (GDP), and water consumption per CN¥ in the Haihe River Basin from the Data Center for Resources and Environment of Sciences, Chinese Academy of Sciences (http://www.resdc.cn/english/default.asp) and considered to remain constant in this study. The irrigation water demand was calculated from the average annual agricultural water use per unit and the area of agricultural land in the grid cell; the industrial water use was calculated from the average annual industrial water consumption per CN¥ of industrial output and the gross domestic product in the grid cell; and the domestic water use was calculated from the average annual domestic water consumption per capita and the population in the grid cell. The proportion of wastewater discharged into streams was arbitrarily set to 30% of the total industrial and domestic water use based on a previous study by Mao et al. (2000). The spatial pattern of the total water demand is shown in Fig. 6.

3.3. Experimental design

We conducted three experiments using the modified RegCM4, and set the simulation periods of all three experiments to 1971–2000. The first experiment, hereinafter referred to as Test 1, applied the estimated water demand in 2000 to the entire simulation period, and the second experiment, hereinafter referred to as Test 2, used half of the water demand applied in the Test 1 and maintained the same water allocation proportions. The third experiment, hereinafter referred to as CTL, was a control simulation that ignored human-induced perturbations.

The RegCM4 was centered at 116°E, 38°N, with a resolution of 30 km × 30 km. ERA40 reanalysis data were applied as the lateral boundary forcing of the model, and the CLM3.5 option and Grell scheme were selected as the model's land surface scheme and convective precipitation scheme, respectively. The time step was set to 100 s for atmospheric processes and 1800 s for CLM4.5.

3.4. Responses of land hydrological and climatic elements to anthropogenic water regulation

We first examined the modeled responses of land hydrological elements to anthropogenic water withdrawal and use. Fig. 7 shows the spatial patterns of differences in 30-year averaged groundwater table depth, soil moisture, and total RG (including surface and sub-surface RG) between Test 1 and CTL and between Test 2 and CTL. In natural conditions, the groundwater table is not expected to show turbulence as equilibrium between precipitation and evapotranspiration is achieved (Yuan et al., 2008). However, in Fig. 7a and b, the groundwater tables in the southern basin deepen by ~10 m in Test 1 and ~5 m in Test 2 by human exploitation. These results indicate that groundwater resources in the basin may be unsustainable and rapidly depleted at the current pumping rate. Even if half of the exploited water amount is reduced, the depletion remains significant. The impacts of over-exploitation on soil moisture, which plays an important role in the hydrological cycle (Liu and Xie, 2013), are shown in Fig. 7c and d. In Test 1, a significant increase in total soil moisture is detected over the entire basin because of heavy irrigation; moreover, the soil moisture outside of the northeastern and southern regions of the basin also significantly increases (Fig. 7c). This result reveals that the effects of land irrigation may spread out of the local area where the water is consumed. When irrigation is reduced by half in Test 2, the effects on soil moisture are not significant, as Fig. 7d shows. Fig. 7e and f illustrate the effects of human water regulation on the total RG. In Test 1, significant differences in RG are detected in the mountainous regions of the north and west, where the groundwater table does not suffer a rapid decline. Because RG

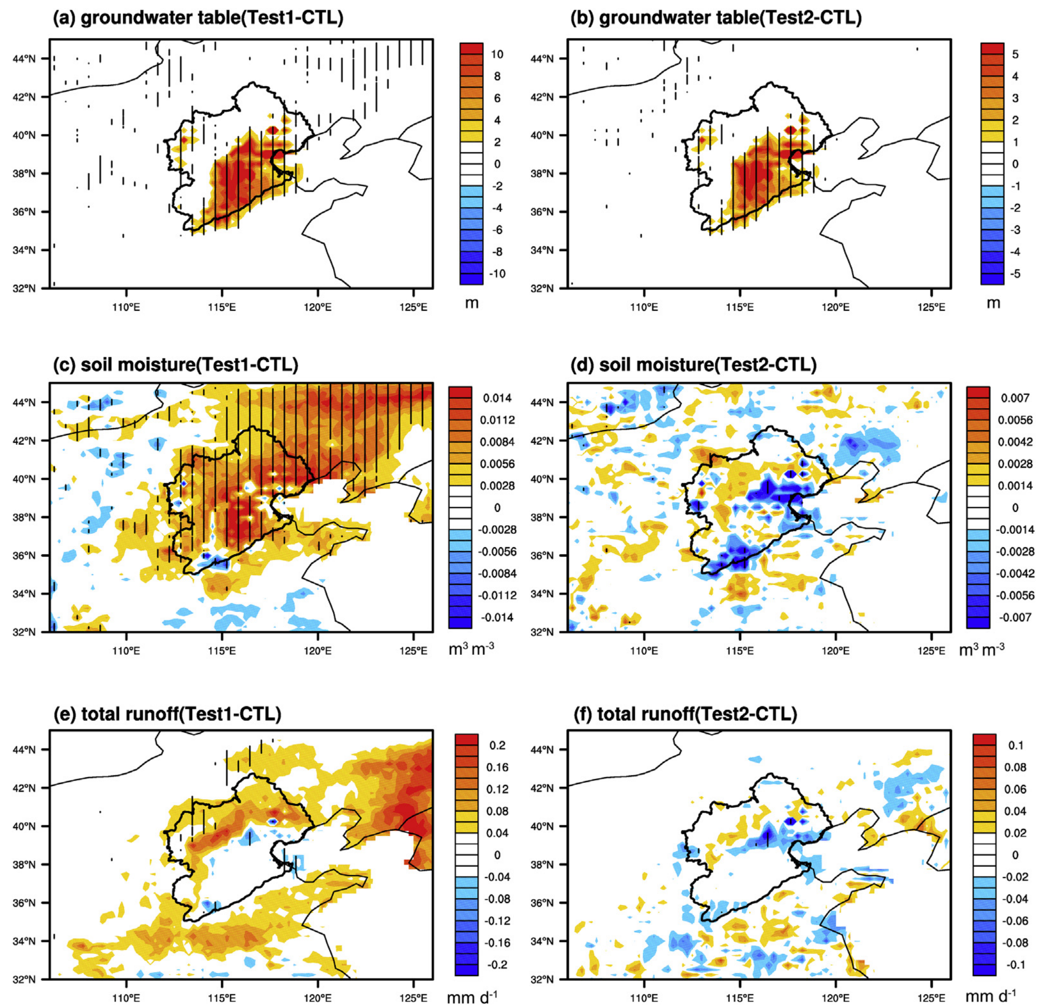

Fig. 7. Spatial patterns of differences in 1971–2000 averaged (a, b) groundwater table depth, (c, d) soil moisture, and (e, f) total runoff generation (a, c, e) between Test 1 and CTL and (b, d, f) between Test 2 and CTL.

is a key indicator of the availability of water resources, the results in Fig. 7e demonstrate the role of human groundwater exploitation on the redistribution of water resources (i.e., water resources are transferred from the south to the north of the basin). In Test 2, the magnitude of the RG difference is much less than that in Test 1, as shown in Fig. 7f. Overall, the impacts of anthropogenic water regulation on soil moisture and RG may be significantly reduced by reducing water use, although impacts on groundwater table (aquifer water storage) may not be easily mitigated.

We analyzed the modeled climatic responses of air humidity, precipitation, wind, and temperature to anthropogenic water withdrawal and use. Fig. 8 shows the spatial patterns of differences in 30-year averaged 850 hPa specific humidity, total precipitation, and convective precipitation between Test 1 and CTL and between Test 2 and CTL. In Fig. 8a and b, human water-related activities (especially irrigation) increase air humidity in both tests. As the air water content increases, the total precipitation in Test 1 also increases, not only within the basin, but also outside of its northeastern and southern portions (Fig. 8c). This increasing effect nearly completely disappears in Test 2 (Fig. 8d), which indicates that precipitation is only impacted when the irrigation rate is high. Fig. 8e and f shows that the effects of human water-related activities on convective precipitation are similar to those on total precipitation, but the magnitude of differences in regions to the northeast of the basin is much lower than that in Test 1; this finding demonstrates that changes in atmospheric circulation likely enhance water vapor transport from the south (i.e., from the ocean) to the northeast of the basin during summer and facilitate large-scale rainfall in these regions instead of increasing local convective activities. Fig. 9 shows summer and winter differences in 850 hPa wind field between Test 1 and CTL and between Test 2 and CTL. In summer, apparent cyclonic differences at 850 hPa are a result of human water application in Test 1 (Fig. 9a), and the wind field is not significantly modified by reducing water use to half the current rate (Fig. 9b). In winter, the northerly wind in the basin is strengthened by human water application in the same test, likely because the cooling effects of water irrigation increase winter temperature differences between the North China Plain and Bohai Sea and strengthen the wind flowing from northern lands to the sea. Wind field differences are negligible in Test 2. Fig. 10 shows the 30-year averaged spatial patterns of

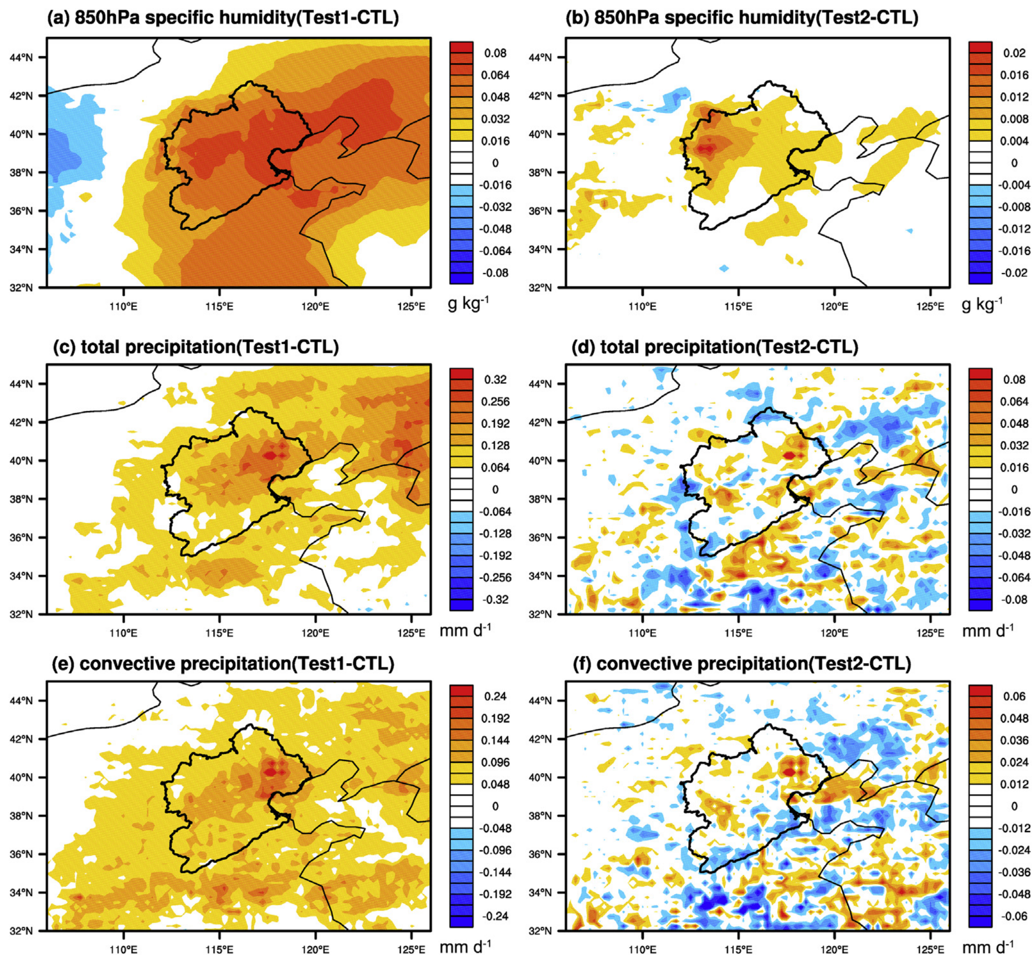

Fig. 8. Spatial patterns of differences in 1971–2000 averaged (a, b) 850 hPa specific humidity, (c, d) total precipitation, and (e, f) convective precipitation between Test 1 and CTL (a, c, e) and between Test 2 and CTL (b, d, f).

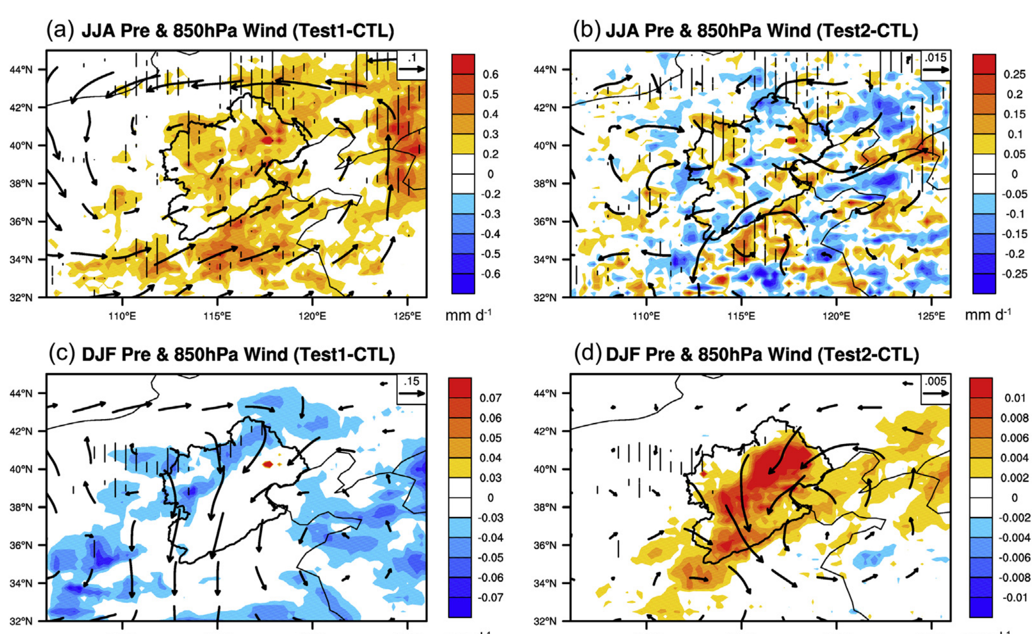

Fig. 9. Spatial patterns of differences in 1971–2000 averaged (a, b) summer 850 hPa wind field, and (c, d) winter 850 hPa wind field between Test 1 and CTL (a, c) and between Test 2 and CTL (b, d).

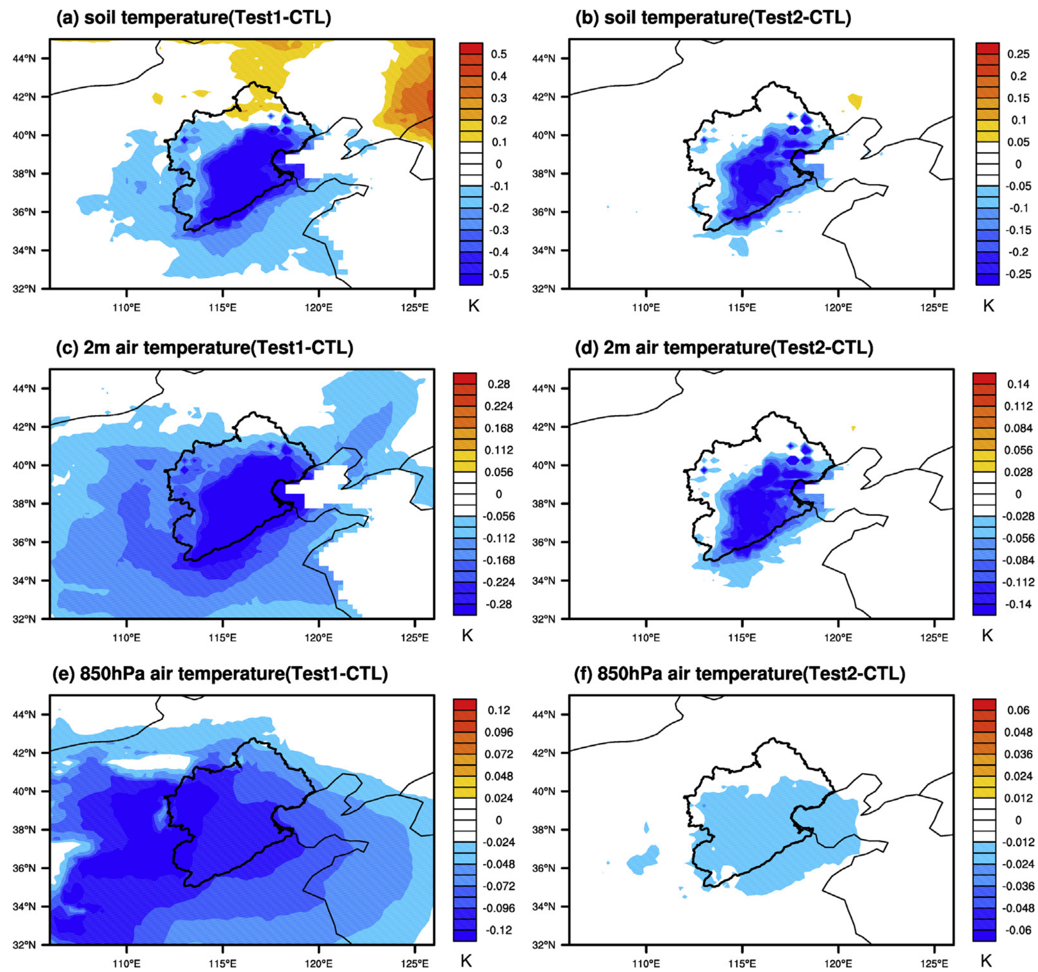

Fig. 10. Spatial patterns of differences in 1971–2000 averaged (a, b) soil temperature, (c, d) 2-m air temperature, and (e, f) 850 hPa air temperature between Test 1 and CTL (a, c, e) and between Test 2 and CTL (b, d, f).

differences in soil temperature, 2-m air temperature, and 850 hPa air temperature between Test 1 and CTL and between Test 2 and CTL in the basin. Fig. 10a–f reveals that soil temperature, 2-m air temperature and 850 hPa air temperature are reduced by human water application (especially agricultural irrigation) for both Test 1 and Test 2. However, cooling effects can extend to outside the basin in Test 1, while cooling effects are mainly restricted within the basin in Test 2. When water application is cut off by half (Fig. 10d), the variation in 2 m air temperature is obviously reduced. Overall, the information in Figs. 7–10 reveals that the impacts of human water withdrawal and use on precipitation and wind field may be significantly reduced by reducing the amount of water extraction and application and that regions affected by anthropogenic water use may be markedly decreased by cutting off human water use rate.

4. Conclusions

Carbon emissions and large-scale anthropogenic water use are two major kinds of human activities. To reveal whether the two intensive human activities can modify the hydrological cycle and climate system in China, we conducted several 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, while 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 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.

The main conclusions of the first study are as follows: 1) NAT significantly increased by over 0.1 °C per decade in most areas across the country between 2007 and 2059 in RCP4.5 scenario. 2) Southwestern and southeastern China showed increasing trends in summer precipitation with increase rates exceeding 10 mm per decade in 2007–2059, although the uncertainty of the prediction is very high. 3) North China showed increasing trends in summer evapotranspiration with increase rates ranging from 1 to 5 mm per decade in most areas; in winter, most regions of China showed significant increasing trends in evapotranspiration. 4) Increasing trends in summer RG occurred in the eastern monsoon region of China, except for the northern China Plain, where the summer RG may be expected to decrease in the future.

The conclusions of the second study are as follows: 1) The groundwater table over the Haihe River Basin, northern China, severely declined by ~10 m because of human over-exploitation in 1971−2000; in fact, the situation appeared to be extreme that even when the pumping rate is decreased by half, groundwater depletion cones remained apparent in the basin. 2) Other hydrological and climatic elements, such as soil moisture, total RG, air humidity, precipitation, wind field, and soil and air temperature, were also significantly affected by anthropogenic water withdrawal and use, but the effects on these elements can be mitigated by reducing water extraction and application.

Future studies will focus on the further application of our developed model to the study of climate−land−human interactions. Other human activities, such as water transfer projects, land use/cover change, and urbanization, will also be included in our model. We will continually improve the descriptions of biogeophysical and biogeochemical processes in our model and apply it to support national policy making for agriculture and water safety.

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