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Detection and attribution of changes in hydrological cycle over the Three-North region of China: Climate change versus afforestation effect

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ABSTRACT

China's Three-North region (TNR), a typical arid and semiarid area, has experienced substantial land cover (LC) changes since the early 1980s partly due to the implementation of large-scale afforestation programs and to expanding urbanization. Hydrological monitoring and simulations for the past five decades reveal that the TNR might have a trend towards environmental degradation due to decreasing soil moisture and streamflow. A few studies regarding individual basins or local scales have proposed that the drying trend is attributable to climate and LC changes; however, little is known about their relative contributions at the regional scale over the TNR. In this study, we employ the Variable Infiltration Capacity (VIC) model in conjunction with remote-sensing retrieval data sets, to detect the changes in hydrological cycle and to identify the contributions of LC and climate change during 1989–2009. The simulation results demonstrate a slight increase in ET at a rate of 3.26 mm per decade over the entire region during 1959–2009. However, ET, runoff and soil moisture exhibit significant decreases after 1989, although their trends have spatial heterogeneities. Sensitivity experiments illustrate that across the TNR, the inter-annual trends in the hydrological regimes can be primarily attributed to the decreasing precipitation which accounts for the ET and runoff declines of 27.5 mm and 16.8 mm, respectively, for the past two decades. The LC change plays a negligible role. These findings are critical to evaluate the effect of ecological projects (e.g., afforestation practices) and imply the importance of water resources management because of the decreasing water availability in this arid and semiarid region. To reduce modeling uncertainties, high-resolution historical LC data sets and model parameterization on dynamic vegetation should be improved.

1. Introduction

The global hydrological cycle is being altered by the changing climate and by human activities with significant consequences for water resources (Oki and Kanae, 2006; Sherwood and Fu, 2014). Climate change is primarily represented by the spatial-temporal redistribution of precipitation and increasing temperature, which together control the water flux and state of land (Frans et al., 2013). Human activities change the hydrological cycle through alteration of land cover (LC), dam and reservoirs constructions, and withdrawal of surface and ground water (Wang and Hejazi, 2011; Xie and Cui, 2011). These changes generally have more serious effects on the hydrological system in arid and semi-arid regions than in humid regions because of increasing drought conditions, increasing extreme floods and a higher frequency of environmental issues (Molnar, 2001).

China's Three-North region (TNR) is an arid and semi-arid area comprised of the north-eastern, northern, and north-western regions, which account for more than half of the total area of China (Fig. 1). The TNR has experienced extensive LC changes over the past decades because of changes in nature and human activities. In the northwest of the TNR, the desert has gradually expanded accompanied by land degradation, which has led to serious desertification and frequent sandstorms (Wang et al., 2010b). The area susceptible to desertification is up to 3.3 million km^2 (Zha and Gao, 1997). To combat the desertification and to control dust storms, the Chinese government has initiated more than five afforestation programs since 1978, including the Three-North Forest Shelterbelt (TNFS) program and the restoration of farmland to forest (Wang et al., 2010b; Wenhua, 2004). The TNFS is a massive afforestation

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program that covers 551 counties in 13 provinces, spanning 70 years. This program was expected to improve forest coverage in the TNR from 5% to 15%, thereby, reducing desertification and dust storms over the next decades. Partly attributed to such afforestation programs, surface cover greenness has actually increased in northern and north-western China during 2000–2010 (Liu and Gong, 2012). In addition to the afforestation programs, northern China is experiencing significant urbanization and industrialization with population growth and rapid economic development, which also have clear effects on climatic and hydrological systems at the local scale (Liu and Xia, 2004).

Along with the LC change, a few studies concerning the local or basins scale have reported significant climate change over the past decades. The climate of northern China has become dryer with increasing temperature (Ma and Fu, 2006). Gauge-observed precipitation has shown fluctuations and a decreasing trend since the late 1980s (Li et al., 2014). In the Tarim river basin (in north-western TNR), trends of increasing precipitation and relative humidity has been observed since 1986 (Tao et al., 2011). Therefore, the climate change pattern has substantial spatial-temporal heterogeneity in the TNR, and the results from the local or basin scale are not representative of the entire TNR.

The hydrological regime has changed across the TNR. Observational and simulation results suggest that annual streamflow has been decreasing in all basins of the TNR since 1960s, except for the Tarim basin and some small catchments (Chen and Liu, 2007; Li et al., 2014; Tao et al., 2011; Wang et al., 2010a; Zhao et al., 2009). Potential evapotranspiration (ET) and actual ET exhibited negative trends during 1960–2002 in northern China (Chen et al., 2005 Gao et al., 2007). The semi-arid area appears to be becoming drier due to slight decreases in soil moisture (Li et al., 2011). These studies consistently focused on basin-scale variations in hydrological variables. The trends of the hydrological variables were analyzed using statistical methods based on a limited number of stations. Statistical methods may not be able to capture the spatial-temporal variability in hydrological variables at the regional scale across the TNR.

Attributing the changes in the hydrological cycle in the TNR is attractive and challenging due to the complex interactions between hydrological systems and environmental conditions. A few studies have focused on detecting the impacts of both climate and LC changes on the hydrology of the TNR. For example, Sun et al. (2006) applied a simplified hydrological model to examine the hydrologic consequences of afforestation on degraded lands, and they suggested that afforestation may reduce the annual water yield in arid and semi-arid regions (such as the Loess Plateau in the TNR). The decrease in the annual water yield is hypothesized to be the result of increased ET due to vegetation cover (Sun et al., 2008). Afforestation programs (e.g., the TNFS program) may have limited effect on improving the ecological conditions, such as combating desertification (Wang et al., 2010b). Forest cover most likely has a negative correlation with the runoff coefficient (Wang et al., 2011b). If afforestation practices in the TNR actually lead to increasing water consumption through ET, the TNR's dry condition will likely be aggravated and have the potential for environmental degradation in this arid and semi-arid region.

Some researchers have emphasized the effects of climate change on the dynamics of the water cycle with respect to individual basins in the TNR. Statistical analyses indicated that there are close and positive correlations between streamflow (or runoff) and precipitation (Li et al., 2014; Tao et al., 2011). Simulation results revealed that climate change may have a greater impact than human activities on hydrological regimes (Cuo et al., 2013a; Tang et al., 2008; Wang et al., 2010a). However, there are specific cases in which climate variability and human activities have approximately equal effects on streamflow (Zhao et al., 2009).

The inconsistencies between these studies regarding the dominant driving forces apparently arise from the different individual basins, time periods, methods, and scenarios employed. The majority of these studies examined the influence of either climate change or of LC change, and thus little is known regarding their relative contributions. None of these studies focused on the hydrological regime at the regional scale across the TNR, although a comprehensive evaluation at the regional scale is critical to the afforestation efforts in the TNR (Sun et al., 2006).

In this study, we attempt to characterize the changes in the hydrological cycle over the past five decades (1959–2009) across the TNR, and to identify the attribution of three hydrological variables, i.e., ET, runoff and soil moisture, to climate and LC changes. We specifically focus on the period from the early stage of afforestation (i.e., 1989) to present, during which there has been a climate change shift. To compensate for the scarcity of hydrological data, we use the Variable Infiltration Capacity (VIC) model (Liang et al., 1994, 1996) to simulate the hydrological processes. Sensitivity experiments are employed to quantify the contributions of each climate factor and LC condition. Note that the term "LC" is simply used to represent "land use and land cover" in this study, although there is minor difference between land cover and land use.

2. Study area and data

2.1. Three-North region

The TNR covers an area of 5.3 million km^2, or 54.8% of China (Fig. 1). This region consists of five large river basins: the Songhua River (SR, 19.6%), Liao River (LR, 5.7%), Hai River (HR, 6.1%), Yellow River (YR, 15.2%) and Inland River (IR, 53.3%) basins from east to west. This region is slightly larger than the area of the TNFS program (4.07 million km^2) (Wang et al., 2010b) because we intend to explore the hydrological cycle at complete basin scales. A large portion of this region lies above the latitude of 35°N. The mean annual air temperature ranges from 20 °C in the south of YR to approximately 0 °C in the north of IR (Fig. 1c). The annual precipitation has an obvious gradient, ranging from 1000 mm in the southeast to less than 100 mm in the northwest (Fig. 1b). Approximately two thirds of the TNR receives less than 400 mm of precipitation. Thus, the IR basin and part of the YR basin are typical arid and semiarid areas and they are susceptible to land degradation, desertification and dust storms (Wang et al., 2010b).

The LC over the TNR has distinct spatial variability. Different types of forest are primarily located in the northeast (i.e., the SR and LR basins) and the north of China (i.e., the HR and YR). A small part of the IR basin, in the northwest of IR, is also covered with deciduous needleleaf forest and mixed forest. This spatial pattern is consistent with the precipitation distribution, and it was partly attributed to the afforestation projects conducted by the Chinese government (Wang et al., 2010b).

2.2. Meteorological data

Daily meteorological data used in this study consist of five variables: precipitation; maximum, minimum and mean temperature; and wind speed for the period 1958–2009. These data were obtained from China Meteorological Administration (CMA, http://cdc.cma.gov.cn/home.do), including 462 stations. These stations were selected based on data quality control to exclude the stations with abnormal values. The spatial distribution of the stations is sparse in the west of TNR, i.e., the IR basin, and relatively dense in the south of TNR, i.e., the YR, HR and LR basins (Fig. 3 in Xie et al., 2007).