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Hydrological response to future climate changes for the major upstream river basins in the Tibetan Plateau

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ABSTRACT

The impacts of future climate change on water balance for the headwater basins of six major rivers in the Tibetan Plateau are assessed using the well-established VIC-glacier land surface hydrological model driven by composite projections of 20 CMIP5 GCMs under scenarios RCP2.6, RCP4.5, and RCP8.5. At the plateau scale, the annual precipitation is projected to increase by 5.0–10.0% in the near term (2011–2040) and 10.0–20.0% in the long term (2041–2070) relative to the reference period 1971–2000. The annual temperature is projected to increase for all the scenarios with the greatest warming in the northwest (2.0–4.0 °C) and least in the southeast (1.2–2.8 °C). The total runoff of the study basins would either remain stable or moderately increase in the near term, and increase by 2.7–22.4% in the long term relative to the reference period, as a result of increased rainfall-induced runoff for the upstream of the Yellow, Yangtze, Salween, and Mekong and increased glacier melt for the upper Indus. In the upper Brahmaputra, more than 50.0% of the total runoff increase is attributed to the increased glacier melt in the long run. The annual hydrograph remains practically unchanged for all the monsoon-dominated basins. However, for the westerly-controlled basin (upper Indus), an apparent earlier melt and a relatively large increase in spring runoff are observed for all the scenarios, which would increase water availability in the Indus Basin irrigation scheme during the spring growing season.

1. Introduction

Major Asian rivers originate from the Tibetan Plateau (TP) and adjacent mountains (Fig. 1), which contains the largest number of glaciers outside the polar regions (Yao et al., 2008). Studies based on meteorological observations, reanalysis data and ice core records have suggested a warming trend (0.16 °C/decade to 0.36 °C/decade) over the TP in recent decades (Thompson et al., 2000; Yao et al., 2000; Liu and Chen, 2000; Frauenfeld et al., 2005; Wu et al., 2007; Xu et al., 2008; Wang et al., 2008). Global climate models from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) also project a warming trend of 0.47 °C/10a to 0.73 °C/10a over the TP in the 21st century under emission scenario RCP8.5 (Su et al., 2013). Along with the warming climate, several studies have reported that the TP glaciers are largely experiencing shrinkage especially in the monsoon-dominated parts of Himalayas (Yao et al., 2004, 2007, 2012; Bolch et al., 2012). The implications of the warming climate and glacier melt in the TP have resulted in a major concern for the water resources downstream (Immerzeel et al., 2010; Kaser et al., 2010).

It was suggested that vanishing glaciers would reduce water supply in the glaciated regions of the TP and adjacent mountains (Barnett et al., 2005). However, the relative importance of meltwater to runoff of major rivers differs fundamentally under different precipitation regimes in the TP (Bookhagen and Burbank, 2010; Immerzeel et al., 2010; Zhang et al., 2013; Bliss et al., 2014). Runoff is influenced not only by glacier- and snow-melt, but also by precipitation. The climate in the TP is mostly dominated by the monsoon systems in the southeast and the westerlies in the northwest. Annual precipitation exhibits an east to west gradient, ranging from over 1500 mm per year in the southeast to less than 100 mm per year in the west (Tong et al., 2014). In the summer months, the southeast monsoon produces heavy precipitation, whereas in the western part, westerly winds cause winter precipitation (Rees and Collins, 2006; Bookhagen and Burbank, 2010). This spatial variability of precipitation influences meltwater regimes, which in turn affect the availability of water for the rivers downstream. Thus, the hydrological response to climate change will be different due to the differences in the source of runoff, climatic conditions and physiological characteristics of the basins.

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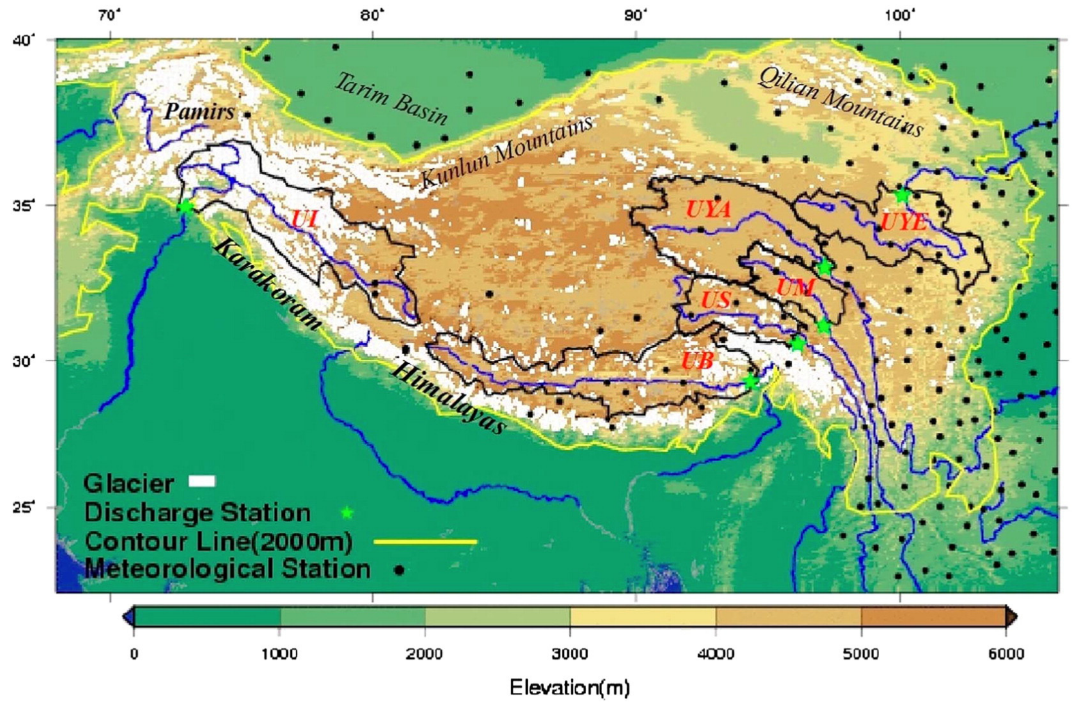

Fig. 1. Topography, rivers (blue lines), boundaries of investigated six basins (black lines) and location of the 176 meteorological stations used for the climate forcing for the period 1971–2000. The UYE, UYA, UM, US, UB and UI represent the upstream of the Yellow, Yangtze, Mekong, Salween, Brahmaputra, and Indus rivers, respectively.

Quantifying the potential impacts of future climate changes on glaciers and river flow over the TP is essential to assist policy-makers and water managers in adopting strategies depending on the state of scientific understanding. A hydrological model driven by hypothetical climatic conditions or climate model projections has been a commonly used approach for assessing the hydrologic consequences of climatic changes. However, most of the existing hydrological impact studies over the TP have focused on branches of the Indus River system (mostly affected by the westerlies) and small Himalayan rivers (Singh and Bengtsson, 2005; Rees and Collins, 2006; Tahir et al., 2011; Jeelani et al., 2012; Immerzeel et al., 2009, 2012, 2013). Less attention has so far been given to a comprehensive understanding of plateau-scale effects. Moreover, uncertainties in climate change scenarios and/or hydrological models have produced large discrepancies among the few available twenty-first century projections of water availability from the TP rivers (e.g., Immerzeel et al., 2010; Lutz et al., 2014). Singh and Bengtsson (2005) investigated the impact of warmer climate on melt and evaporation of a branch of the Indus River system using a conceptual snowmelt model. The results suggest a reduction of 18% of melt water from snowfed basins and an increase of 33% from glacierfed basins under an assumed temperature scenario ($t + 2$ °C). Rees and Collins (2006) investigated the regional differences in response of flow in glacier-fed Himalayan rivers with a temperature-index-based hydro-glaciological model under a uniform warming scenario (0.06 °C year^{-1}) and suggested that the melt water component in the total runoff would rapidly decrease from west to east. Immerzeel et al. (2009) assessed the effects of climate change on streamflow of upper Indus using the Snowmelt Runoff Model (SRM) with a regional climate model's projections under assumed glacier extent scenarios. The total runoff of the upper Indus was projected to increase 7% by the end of 21st century relative to 2001–2005 under a 50% decrease of glacier extent scenario. Using the same SRM model, Immerzeel et al. (2010) provided an assessment of future water availability from five river basins (Indus, Brahmaputra, Ganges, Yellow, and Yangtze rivers) in the TP under different climate and glacier area scenarios. Their results suggest that all the basins except the Yellow would have a decrease in mean annual flow over the period 2046–2065 relative to 2000–2007. A more recent study (Lutz et al., 2014) using a distributed cryospheric-hydrological model and an ensemble of the latest GCM outputs, however, projects an increase in runoff at least until 2050, due to primarily an increase in precipitation in the upper Ganges, Brahmaputra, Salween and Mekong basins and accelerated melt in the upper Indus Basin. The

Table 1
Characteristics of the six source river basins in the Tibetan Plateau. Glacier areas are based on a dataset from the “Environmental & Ecological Science Data Center for West China” (http://westdc.westgis.ac.cn/data/ff75d30a-ee7d-4610-a5a3-53c73964a237) and the Randolph Glacier Inventory (http://www.glims.org/RGI/).

Basins		Yellow	Yangtze	Mekong	Salween	Brahmaputra	Indus
Control stations		Tangnaihai	Zhimenda	Changdu	Jiayuqiao	Nuxia	Besham
Location	Latitude (°N)	35.30	33.02	31.11	30.51	29.27	34.92
	Longitude (°E)	100.09	97.13	97.11	96.12	94.34	72.88
Drainage area (km^2)		121,972	137,704	53,800	69,384	191,235	164,867
Percent of total basin area (%)		16.22	7.61	6.77	20.91	30.89	13.91
Glacier area (km^2)		134.16	1308.19	225.96	1151.58	4225.20	15,325.20
Percent of drainage area (%)		0.11	0.95	0.42	1.70	2.10	9.46

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