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Review

An overview of studies of observed climate change in the Hindu Kush Himalayan (HKH) region

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Abstract

The Hindu Kush Himalayan (HKH hereafter) region is characterized by mountainous environments and a variety of regional climatic conditions. High-altitude regions in the HKH have the recent warming amplifications, especially during the global warming hiatus period. The rapid warming cause solid state water (snow, ice, glacier, and permafrost) to shrink, leading to increase in meltwater and there have been found more frequent incidences of flash floods, landslides, livestock diseases, and other disasters in the HKH region. Increasing awareness of climate change over the HKH region is reached a consensus. Meanwhile, the HKH region is often referred to as the water towers of Asia as many high-altitude regions store its water in the form of snow and/or glacier, feeding ten major large rivers in Asia. Therefore, the impacts of climate change on water availability in these river basins have huge influences on the livelihood of large number of population, especially in downstream regions. However, the scarcity of basic hydro-meteorological observations particularly in high-altitude regions of HKH limits rigorous analysis of climate change. Most studies used reanalysis data and/or model-reconstructed products to explore the spatial and temporal characteristics of hydro-meteorological processes, especially for extreme events. In this study, we review recent climate change in the HKH region, and the scientific challenges and research recommendations are suggested for this high-altitude area.

Keywords: Climate change; Hindu Kush Himalayan; Tibetan Plateau; Hydrological cycles

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1. Introduction

According to the IPCC Fifth Assessment Report (IPCC, 2013b), global mean surface temperatures have risen by 0.84 °C since 1880, which have substantial ecological, economic and societal impacts. The Hindu Kush Himalayan (HKH) region encompassing more than 4.3 million km^2 area includes areas of Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan, as well as comprises of many of the Earth's highest mountains and most extensive basins, including the Tianshan Mountains, Himalayas, Pamir, Hengduan Mountains, and Changtang Plateau, and is one of the greatest mountain systems in the world (Sharma et al., 2016). These mountains in the HKH region are often referred to as the water towers of Asia and

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many high-altitude regions store water as snow and/or glacier, forming a region of perplexing hydroclimate changes. Ten major river basins originating from the HKH are Yangtze, Yellow, Mekong, Salween, Irrawaddy, Brahmaputra, Gangers, Tarim, Indus, and Amudarya Rivers, respectively. Consequently water availability in these river basins has a huge influence on the livelihood of great human population on this planet. Moreover, the HKH region has an estimated area of 60,000 km^2 of glaciers (Miller et al., 2012), and contains the largest area of land permanent ice cover in the world. Outside of the North and South Poles, the HKH region is referred as the Third Pole of the earth, and provides ecosystem services sustaining the livelihoods of 210 million people directly (Sharma et al., 2016). The HKH region is characterized by some of the most complex terrain, and has a substantial influence on the East Asian monsoon, and even on global atmospheric circulation (Sharma et al., 2016; Qiu, 2008; Yanai and Li, 1994; Yao et al., 2012a). Due to its diverse and fragile natural environment, the impacts related to climate warming on the HKH region are well evident, including glacier retreat, inconsistent snow-cover change, increase in permafrost temperatures and degradation, and thickening of the active layer, and the hydrological processes impacted by glacial retreat have received much attention in recent years (Barnett et al., 2005; Kang et al., 2010; Pepin et al., 2015; Qiu, 2008; Sarıkaya et al., 2013).

In recent years, the glaciers and snowfields of the HKH region are found to be the fastest receding glacier and snow covers in the world (Mukhopadhyay, 2012; Prasad et al., 2009). The river basins within the HKH that are covered by perennial snow and ice form a complicated hydrological cycle system where contributions from snow, ice, frozen soil, and glacier melts to river discharge are significant. These basins are extremely sensitive to climate change in terms of spatial and temporal characteristics. Snow, ice, and glacier in the HKH are sensitive to climate change (Kumar et al., 2015); therefore, these variables constitute a significant component of the river flows in all of the HKH river basins. The percentages of melt water from permanent snow and glacier in river flows are different from each river. Some of lakes in the HKH can burst out flash floods caused by the ongoing retreat of glacier (Shrestha et al., 2010), damaging buildings and infrastructure.

The HKH region is undergoing climate change, and is critical and sensitive to climate change under the background of global warming. In this paper, the observed changes in climate elements in the HKH region were firstly reviewed, focusing on rapid warming, climate extremes and elevation-dependent warming. Then hydrological response to climate change in the HKH region was overviewed. Finally, outlook and conclusions were recommended.

2. Observed changes in climate elements in the HKH region

2.1. Rapid warming in the HKH region

The Tibetan Plateau (TP) occupies the major HKH region, and is a representative area for this region. Based on observation, reanalysis and remote sensing and the coupled model intercomparison project phase 5 (CMIP5) model outputs, the TP showed significant warming in recent decades and this warming trend will last in the future (Duan and Xiao, 2015; Kang et al., 2010; Kuang and Jiao, 2016; Liu and Chen, 2000; Liu et al., 2006, 2009; Wang et al., 2008; Yao et al., 2012b; You et al., 2016; You et al., 2013a). Linear rates of temperature increase over the entire TP during 1955–1996 are about 0.16 °C per decade for the annual mean and 0.32 °C per decade for the winter mean, which exceeded the averages for the Northern Hemisphere and the same latitudinal zone (Liu and Chen, 2000). In recent, Yan and Liu (2014) reported a warming trend of 0.316 °C per decade in annual mean temperature in the TP for the period 1961–2012, which doubles the previous estimation by Liu and Chen (2000). During the recent studies by the updated observations and from the historic CIMP5 outputs (Kang et al., 2010; You et al., 2013a, 2016), the annual mean surface temperatures in the TP have doubled the previous warming rate. This rapid warming in the TP is primarily owing to the more and warmer data for the last decade and during the global warming hiatus period (You et al., 2016). Meanwhile, the asymmetric pattern of greater warming trends in the minimum temperature than in maximum temperature found in the TP (Liu et al., 2006, 2009). According to the SRES A1B scenario (a middle of the road estimate of future emissions), a 4 °C warming will be likely to occur over the TP during the next 100 years (Kang et al., 2010), and the warming in the TP from the observation and CMIP5 models is more sensitive and accelerated during the hiatus period and in future projections (You et al., 2016). The accelerated climate warming over the TP has caused significant glacial retreat, snow melt, and permafrost degradation (Kang et al., 2010; Yao et al., 2012a, 2012b), and will also lead to significant changes in hydrology and water resources on the TP (Immerzeel and Bierkens, 2012; Immerzeel et al., 2010; Kuang and Jiao, 2016; Yang et al., 2014). Climate warming can cause shrinkage in the overall glacier mass, providing increases in meltwater contribution to downstream river flows in particular during the rapid warming seasons. Some glacier lakes in the HKH region have expanded rapidly caused by climate warming and glacier retreat (Wang et al., 2015).

2.2. Trends in climate extremes in the HKH region

During 1961–2005, temperature extremes in the TP show patterns consistent with warming, with a large proportion of stations showing statistically significant trends for all temperature indices. Stations in the northwestern, southwestern, and southeastern TP have larger trend magnitudes. The regional occurrence of extreme cold days and nights has decreased at −0.85 and −2.38 d per decade, respectively. Over the same period, the occurrence of extreme warm days and nights has increased at 1.26 and 2.54 d per decade, respectively. The number of frost and ice days shows statistically significant decreasing at the rate of −4.32 and −2.46 d per decade, respectively. The length of growing season has statistically increased by 4.25 d per decade. The diurnal temperature range exhibits a statistically decreasing trend at a rate of −0.20 °C per decade. The extreme temperature indices also show statistically significant increasing trends, with larger values for the index describing variations in the lowest minimum temperature. In general, warming trends in minimum temperature indices are of greater magnitude than those for maximum temperature (You et al., 2008b). The western part of the Indus River Basin presented significantly downward trends in extreme precipitation whereas the eastern (Transhimalaya and Himalayas) and the northern (Hindu Kush and Karakoram) part of the Indus Basin showed obviously increasing trends (Hartmann and Buchanan, 2014). More extreme conditions consistent with a warmer, wetter climate exist in the HKH region. There is more frequent extreme precipitation during monsoon season in the eastern Himalaya, and a wetter cold season in the western Himalaya-Karakoram (Panday et al., 2015).

2.3. Elevation-dependent warming in the HKH region

The temperature in the HKH undergoes a significantly increasing trend, and the warming rate in the HKH region is greater than the globe and China (Table 1). Thus, the elevation-dependent warming (EDW) is clear over the TP, and the warming has occurred at a greater rate at higher elevations (Duan and Xiao, 2015; Guo et al., 2016; Pepin et al., 2015; Ren et al., 2005; Yan and Liu, 2014; Yan et al., 2016; You et al., 2016). For example, Yan and Liu (2014) analyzed the change in trends of mean, maximum and minimum temperatures over the TP, and reported a warming trend of 0.316 °C per decade in annual mean temperature over the TP for the period 1961–2012, based on the 73 stations above the elevation of 2000 m a.s.l. in the TP. They also examined the elevation-dependent warming in the TP. Liu and Chen (2000) revealed a more pronounced warming at high elevations when compared with surrounding regions in the TP, which has since been confirmed by numerical experiments (Chen et al., 2003) and such a tendency may continue in future climate change scenarios (Liu et al., 2009). These all do not come to the same conclusions, probably because of differing datasets, periods of analysis, and lowland stations used for comparison (Kang et al., 2010). Using temperature trend magnitudes at 71 surface stations with elevations above 2000 m a.s.l. in the eastern and central TP (You et al., 2008a) fail to capture an elevation dependency in the trends of temperature extremes in the eastern and central TP.

The exact driving mechanisms responsible for EDW need further investigation. Yan et al. (2016) concentrated on EDW mechanisms over the TP, and concluded that the increase in surface net radiation resulted greater in EDW over the TP. One possible reason for the continued (and accelerated) warming in the TP is positive feedbacks associated with a diminishing cryosphere. You et al. (2010a) summarized the factors determining the recent climate warming in the TP: anthropogenic greenhouse gas emissions, the snow/ice-albedo feedback, and changes of environmental elements (such as cloud amount, specific humidity, Asian brown clouds and land use changes). Furthermore, although it is currently difficult to determine the relative contribution of each of these factors, the anthropogenic greenhouse gas emission is regarded as the main cause of the warming in the TP, and their impacts are probably more serious than the rest of the world (Kang et al., 2010; You et al., 2010a). The TP has the largest cryospheric extent (glaciers and ice caps, snow, river and lake ice, and frozen ground) outside the polar region (Kang et al., 2010). The glaciers have exhibited a rapid shrinkage in both length and area in recent decades (Yao et al., 2012b), coinciding with the rapid warming in the TP.

2.4. Changes in other meteorological elements

2.4.1. Ununiformed change in precipitation

Precipitation in the TP (You et al., 2015) is slightly increased since the 1960s, and the TP is overall getting wetter (Kuang and Jiao, 2016). The TP is overall getting warmer and

Table 1
Summary of temperature trends obtained from observed studies in the HKH region.

Reference	Region	Time period	Parameter	Trend (°C per decade)
Liu et al. (2009)	Tibetan Plateau (TP)	1961–2006	Annual Tmin	0.42
			Tmin in winter	0.61
Liu et al. (2006)	Eastern and central TP	1961–2003	Annual Tmin	0.41
			Annual Tmax	0.18
Liu and Chen (2000)	TP	1955–1996	Annual temperature	0.16
			Winter temperature	0.32
Yan and Liu (2014)	TP	1961–2012	Annual temperature	0.32
You et al. (2010a)	TP	1951–2004	Annual temperature	0.25
Gautam et al. (2010)	Western Himalaya	1979–2007	Annual temperature	0.26
Eriksson et al. (2009)	Nepal	1977–2000	Annual temperature	0.60
Duan and Xiao (2015)	TP	1980–2013	Annual temperature	0.44
	China	1980–2013	Annual temperature	0.35
Ren et al. (2005)	China	1951–2001	Annual temperature	0.22
IPCC (2013a)	Globe	1951–2012	Annual temperature	0.12

wetter during the recent decades. The precipitation in the TP is slightly increased, but the increase is not as pronounced as that of temperature. However, the spatial pattern of changes in precipitation is complicated, and the annual precipitation does not show a uniform increasing or decreasing trend across the TP (Kuang and Jiao, 2016; You et al., 2015). Compared with observations, most of the datasets (NCEP1, NCEP2, CMAP1, CMAP2, ERA-Interim, ERA-40, GPCP, 20century, MERRA and CFSR) can both broadly capture the spatial distributions and identify temporal patterns and variability of mean precipitation in the TP (You et al., 2015). Over the Himalaya during the summer, the evolution of precipitation under two different future scenarios (RCP 4.5 and RCP 8.5) reveals an increasing trend, associated with an increase in wet extremes and daily intensity and a decrease in the number of rainy days (Palazzi et al., 2013). There is no single CMIP5 model provides the best simulation in precipitation, and the large spreads of individual models suggest to consider multi-model ensemble means with extreme climate (Palazzi et al., 2015).

2.4.2. Decrease in wind speed

The declining trend of the surface wind speed prior to 2003 over the TP was earlier reported by Duan and Wu (2008). The reanalyses also have the decreased wind speed in the TP. During 1980–2005, both surface stations and NCEP/NCAR reanalysis in the TP show significant decreasing trends at rates of -0.24 and -0.13 m s^{-1} per decade, respectively, mainly evident in spring and summer (You et al., 2010b). ERA-40 fails to capture any decrease. The most likely causes of diminishing wind speed are the asymmetrically decreasing latitudinal surface temperature and pressure gradients over the TP, which may be part of a large-scale atmospheric circulation shift (You et al., 2010b). Furthermore, the increase in wind speed after the 2000s may indicate the overall change in atmospheric circulation over East Asia (Yang et al., 2014).

2.4.3. Decrease in solar radiation and sunshine duration

The declined surface solar radiation (SSR) associated with climate warming over the TP has also been documented (Yang et al., 2011). Based on the surface observational data, reanalyses and ensemble simulations with the global climate model ECHAM5-HAM, the mean annual all-sky SSR series in the TP shows a decreasing trend of -1.00 W m^{-2} per decade, which is mainly seen in autumn and secondly in summer and winter. A stronger decrease of -2.80 W m^{-2} per decade is found in the mean annual clear sky SSR series, especially during winter and autumn (You et al., 2013b). The temporal evolution of the mean annual sunshine duration series shows a significant increase from 1961 to 1982 at a rate of 49.8 h per decade, followed by a decrease from 1983 to 2005 at a rate of -65.1 h per decade, with an overall significant decrease at a rate of -20.6 h per decade during the whole 1961–2005 period, which is mainly due to the summer and spring seasons. This confirms the evidence that sunshine duration in the TP ranges from brightening to dimming in accordance with sunshine duration trends in the rest of China (You et al., 2010c). Total and low-level cloud amounts show contrasting trends during day and night, with decrease during daytime but increase (especially low-level cloud) at night (Duan and Wu, 2006). Dust deposition on snow/glacier can change the surface albedo, resulting perturbations in surface radiation balance. Ji et al. (2016) found that a positive surface radiative forcing was induced by dust (including aerosol-snow/ice feedback), resulting in temperature increase of 0.1–0.5 °C over the western TP and Kunlun Mountains from March to May.

3. Hydrological response to climate change in the HKH region

The HKH includes the five major Southeast Asian basins: Yangtze, Ganges, Indus, Yellow, and Brahmaputra River Basins. Therefore, the HKH is a crucial area in terms of water resources, but the understanding of the response of its high-elevation basins under climate change is hindered by lack of hydro-meteorological and cryospheric data (Pellicciotti et al., 2016). It is necessary to predict spatial and temporal (especially for future predictions) hydrological process using physically and distributed hydrological models. However, hydrological modeling is challenging in this region because both data scarcity and internal inconsistency (i.e., complexity of feedback mechanisms that govern melt and runoff generation). Pellicciotti et al. (2016) used snow-cover remote imagery and limited discharge data to calibrate hydrological model parameters for simulating stream flow and other water balance variables of remote Himalayan headwaters (Hunza River Basin in Pakistan). Miller et al. (2012) selected three major basins (Ganges, Brahmaputra, and Indus) as examples to provide an overview of the variability in glacier hydrological response. Afterwards they gave several recommendations such as improvement of precipitation data in high-altitude basins, quantification of the spatial variation in glacier and snowmelt, and development of glacial-hydrological models to accurately simulate water and energy balance in HKH. Quantification of the contribution of hydrological components (snow, ice and rainfall) to river discharge in the HKH region is important for decision-making in water sensitive sectors, and for water resources management and flood risk reduction. Brown et al. (2014) presented a case study from the Langtang Khola Basin in the monsoon-influenced catchment of Nepal Himalaya, and concluded that the total surface water input in this basin was 62% from glacier melt, 30% from snowmelt, and 8% from rainfall. Estimation of snow and ice covered areas within the upper Indus Basin shows that there is a decline (about 2.15% reduction) from 1992 to 2010, furthermore, the peak discharge time has shifted from middle/late summer to late spring/early summer as another outcome of snow and ice covered areas reduction (Mukhopadhyay, 2012). Shrestha et al. (2010) took Sun Koshi Basin (a transboundary river basin between China and Nepal) as an example for evaluating glacier lake outburst flood risk to support proper planning of mitigation and adaptation strategies in the HKH region. In recent years, there have been more frequent incidences of floods, droughts, landslides, livestock diseases, and crop pests in the HKH region, and have attributed these to climate change (Hussain et al., 2016).

Global/regional warming and the deposition of light-absorbing impurities may reduce the HKH glacier area (Gautam et al., 2013; Gertler et al., 2016; Ming et al., 2015). A relatively rapid decrease in the surface albedo occurs in higher glacier, and this decrease is related to the snow melt in the HKH region, forming a positive feedback that accelerates the melting process to occur (Ming et al., 2015), yet undeniable impacts of climate change (Bajracharya et al., 2015). Seasonal cycle in different parts of the HKH is also important to climate variables, for example, a unique seasonal cycle makes snowfall less sensitive to warming in Karakoram than in Himalayas (Kapnick et al., 2014). The seasonal cycle of snow depth with a maximum in February−March almost completes melting in summer, with a significant reduction in the spatial average of snow depth over the HKH in the future (Terzago et al., 2014). The eastern Himalayan glaciers (Nepal−Bhutan) are most vulnerable to climate change due to the deceased snowfall and increased ablation associated with warming (Wiltshire, 2014). Glacier lakes in the HKH have been expanding as a result of glacier recession, and may induce outburst flood risks for downstream populations (Khanal et al., 2015). The mechanisms of this hydro-meteorological process are needed to study and establish monitoring and early warning systems.

4. Outlook and conclusions

Mountainous conditions are generally considered sensitive indicators of climate change, and the climate change in the HKH region needs to attract more attention for making appropriate decisions (Barnett et al., 2005; Immerzeel et al., 2010; Kang et al., 2010; Liu et al., 2006, 2009; Shea and Immerzeel, 2016). The HKH experienced an overall rapid warming during the global warming period and the warming hiatus period, which further influenced the climate extremes and hydrological cycles in the regions. Owing to the high altitude, complex topography, and extreme climatic conditions, the consistent long-term hydro-climatological observations and sufficiently dense networks of meteorological stations covering all high-altitude areas of HKH are limited, some studies used reanalysis data and/or model-reconstructed products to explore the spatial and temporal characteristics of extreme climate events (Hartmann and Buchanan, 2014; Palazzi et al., 2015). Other variables in HKH region are also scarce, especially for snow and glacier data. Kääb et al. (2012) used indirect method (satellite laser altimetry and a global elevation model) to explore glacier patterns in the HKH, and found that maximal regional thinning rates were 0.66 ± 0.09 m per year in the Jammu-Kashmir region. Elevated temperatures cause permafrost and glaciers to decline in much of the HKH, and also result in temporal melting such as snow melt begins earlier and winters are shorter.

A highly data sparse region limits the proper cross validation of regional climate model results, which calls for global, regional, and national endeavor to fill the gap. Climate warming and ununiformed precipitation patterns across the HKH region have an important influence on water resources and food security for the downstream population (Rasul, 2014). There are no corroborated trends exist in observed discharge for any basins in the HKH, and such analyses are hindered by a lack of good quality long-term data (Miller et al., 2012). Elevated temperature will cause glacier to shrink, leading to increase in melt water caused by subsequent decline with reduced glacier mass. Increased uncertainties in surrounding precipitation and socioeconomic changes limit any conclusive assessment of how water availability will be affected. The combination of higher snowfall and rapid melting may favor the occurrence of flash floods; permafrost melting may induce rock avalanches down the steepest cliffs and might impact the adjacent valley floors (Fort, 2015). Kulkarni et al. (2013) applied regional climate model (Providing Regional Climates for Impact Studies, PRECIS) to examine the potential impact of climate warming in the HKH region.

Fundamentally, it is the scarcity of observed data on precipitation, glacier melt, and river discharge in particular in high-altitude regions of HKH that limits rigorous analysis of change. Uncertainty in climate and hydrological models to climate warming further limits the confidence that can be ascribed to modeling of future change. In Tamakoshi Basin (HKH region), the spring and winter snow covers are more vulnerable to climate change, the proportion of snowmelt runoff will be increased in the future (Khadka et al., 2014). In sub-basins of HKH, glacier contributions to stream flow increase by about 50% for a Kevin warming based on a static geometry, and a majority of the basins will experience decreasing glacier contributions by the end of the 21st century (Shea and Immerzeel, 2016). Snowmelt fraction is slightly greater than the glacier melt fraction in upper Indus Basin of HKH (Mukhopadhyay and Khan, 2015). According to CMIP5 models, snowmelt is projected to occur earlier, while the ice melt component is expected to increase, with ice thinning considerably and even it will disappear below 4000 m until the end of the 21st century (Soncini et al., 2015). Despite many studies focus on the HKH, the assessment of climate change impact on hydrological process is still subject to great uncertainty. One of the major uncertainties is the climatic and hydrological model due to scarce data in high-altitude regions of HKH. Therefore, it is necessary to have comprehensive studies of hydro-meteorological process in the HKH because climate change and hydrological cycle might have induced natural hazards in this region. It is needed to strengthen the construction of observation networks to obtain more basic meteorological data in the HKH, especially precipitation data that can be used to improve climatic and hydrological model. Then, it is required to optimize the climatic and hydrological model, and to improve the prediction accuracy. It has also promoted the cooperation to face the challenges on the impacts of climate and hydrology change.

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