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Review

Climate change in the Hindu Kush Himalaya

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The Hindu Kush Himalaya is the highest mountainous and plateau system in the world, sitting on most of the world's highest peaks over 8000 m in height (Fig. 1). This region encompasses an area of more than 4.3 million km^2 and is characterized by a diversity of physiographic landscapes, climate types and bio-systems, the largest cryosphere in the world beyond the two poles, and being the source of a number of highly important large rivers including the Brahmaputra, Ganges, Indus, Mekong, Yangtze, and Yellow Rivers. The HKH is populated by about 210 million people and an additional 1.3 billion people live in downstream basins of the ten large rivers originating from this region.

Obvious climate changes have occurred in the HKH and may have exerted a large impact on its natural and human systems, as reported by many research groups and the IPCC (Singh et al., 2011; IPCC, 2013; You et al., 2017). Our understanding of climate change and its impact is better in a few areas, including the eastern Tibetan Plateau (TP), the Yunnan-Guizhou Plateau, and the low-lying plains of northern India. In most of the other areas, however, research has been relatively scant due to the big data gap. There are few high-quality historical observational data for these areas and a lack of human capacity for dealing with and analyzing observational and modeling data. In particular, as yet, there has been no analysis of past climate changes in the HKH as a whole and this prevents an in-depth understanding of climate change and its mechanism and the validation of climate models and their application in projecting future climate scenarios in this highly vulnerable region.

A comprehensive assessment of the HKH is underway as part of the larger Hindu Kush Himalaya Monitoring and Assessment Program (HIMAP). This assessment will consider many critical questions, including chapters on observed and projected HKH climate change and how climate change will impact the mountainous glaciers, water resources, and ecosystems of the region. The climate change chapter will present a broad overview of the weather and climate elements pertaining to the HKH, focusing more specifically on the linkages of large-scale drivers of climate change and variability in the region, past and present regional climate variations including extreme weather and climate change, and the projections of future climate using global and high-resolution regional climate models. Because no publication of observations of the overall HKH are available, a series of analyses have been conducted using recently developed global land climate datasets by the China Meteorological Administration (CMA) in combination with an assessment of previous publications on different areas of the HKH. A reanalysis of modeled outputs from global and regional models has also been conducted to determine likely future climate scenarios in the region. Since these results are new and very pertinent, it is therefore necessary to publish them as peer-reviewed papers.

This special issue includes seven papers. One is an overview of recent research in the HKH (You et al., 2017), three discuss observed climate changes over the past century or more (Ren et al., 2017; Sun et al., 2017b; Zhan et al., 2017), and three address projected future trends of climate under various representative concentration pathways (RCPs) (Wu et al., 2017; Sanjay et al., 2017; Rajbhandari et al., 2017). We summarize the main findings of these papers as follows (also see Table 1).

You et al. (2017) gave an overview of climate change observations in the HKH. They reported some consensus regarding recent climate change in the HKH for the TP in particular, as reported over the past decade, and also note the current scientific challenges and make research recommendations. This overview confirms the significant annual and

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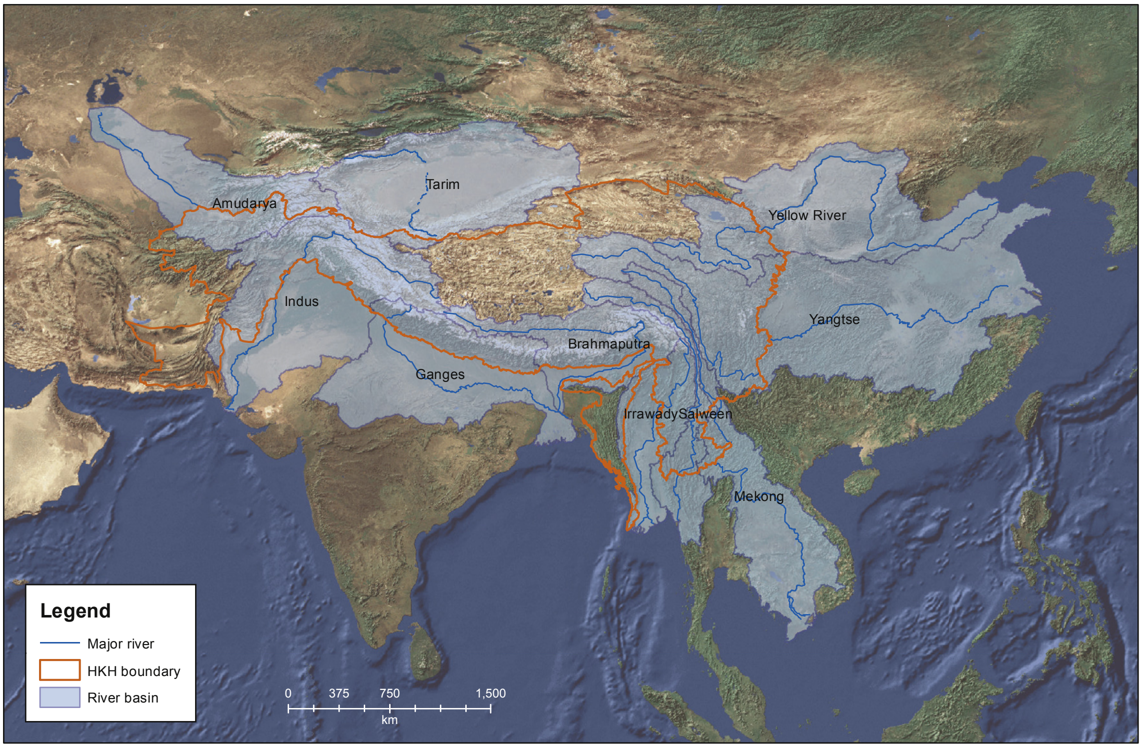

Fig. 1. Hindu Kush Himalaya and the major rivers originating from it.

Table 1
Observed changes in mean and extreme climates over the HKH during 1901—2014 and 1961—2015 (summarized from Ren et al. (2017); Sun et al. (2017b); Zhan et al. (2017)).

Indicator	Index	ID	Period	Trend direction	Trend value	Unit	Uncertainty level
Mean temperature and total precipitation	Mean temperature	T_{mean}	1901—2014	⬆	0.104	°C per decade	M
			1951—2014	⬆	0.195	°C per decade	L
	Total precipitation	P_{total}	1901—2014	⇩	−0.360	% per decade	H
	Total precipitation		1961—2013	⬆	3.529	% per decade	M
Extreme temperature event	Cold nights	TN10p	1961—2015	⬇	−0.977	d per decade	M
	Cold days	TX10p	1961—2015	⬇	−0.511	d per decade	M
	Warm nights	TN90p	1961—2015	⬆	1.695	d per decade	M
	Warm days	TX90p	1961—2015	⬆	1.239	d per decade	M
	Frost days	FD	1961—2015	⬇	−3.636	d per decade	M
	Summer days	SU	1961—2015	⬆	6.741	d per decade	M
Extreme precipitation event	Intense precipitation	IPA	1961—2012	⬆	6.16	% per decade	H
	1-d maximum precipitation	RX1DAY	1961—2013	⬆	2.14	% per decade	H
	3-d maximum precipitation	RX3DAY	1961—2013	⬆	2.26	% per decade	H
	5-d maximum precipitation	RX5DAY	1961—2013	⬆	2.34	% per decade	H

Note: Arrows indicate upward and downward trends, with the solid arrow indicating a significant trend ($p < 0.05$). Uncertainty levels of H (high), M (medium), and L (low) denote that the uncertainties of the estimates mainly due to data coverage and quality are large, moderate, and small, respectively.

winter warming in the TP region and also shows that amplified climate warming or so-called elevation-dependent warming (EDW) has seemed to occur over the TP. However, this phenomenon also seems to be regional and time dependent, with the TP and its surrounding areas having witnessed the clearest EDW over the last two decades. During the past two decades, which has been referred to as the global warming slowdown or hiatus, the annual and cold-season mean surface air temperatures over the TP have continued to increase, whereas the surface air temperature of northern and eastern China has experienced a remarkable leveling off or even decline in a few areas (Li et al., 2015; Sun et al., 2017a).

Ren et al. (2017) showed that during 1901—2014, the annual mean surface air temperature significantly increased in the HKH as a whole. The warming rates, in terms of annual mean surface air temperature, annual mean maximum temperature, and annual mean minimum temperature, reached 0.104 °C per decade, 0.077 °C per decade, and 0.176 °C per decade, respectively. The annual mean surface air temperature increase is similar to that of the global average, but the annual mean minimum temperature increased by more than twice the annual mean maximum temperature, leading to more asymmetrical warming between day and night in this region. Annual warming has been observed in most parts of the HKH, with the greatest warming occurring in the TP and south of Pakistan.

Ren et al. (2017) also showed that the precipitation trend of the whole HKH is characterized by a slight decrease over the past 100 years, but this decrease is insignificant. During the last six decades, however, the regional average annual total precipitation exhibited a statistically significant increase at a rate of 5.28% per decade, and the annual precipitation has increased more rapidly since the mid-1980s. Most parts of India and the northern TP have seen a more obvious increase in the annual precipitation days, but the areas of southwestern China and Myanmar are experiencing a declining trend. The annual mean precipitation intensity has seemed to increase at higher altitudes in the HKH in recent decades.

Sun et al. (2017b) reported their analysis results of extreme temperature change in the HKH over the last six decades based on a multi-source daily temperature dataset (GLASTD V1.0) recently developed by CMA. Extreme cold events (cold days, cold nights, and frost days) have significantly decreased and extreme warm events (warm days, warm nights, and summer days) have significantly increased in the region overall during the 1961−2015 period. In addition, the trends of extreme events related to minimum temperature (Tmin) have been generally greater than those related to maximum temperature (Tmax). With respect to absolute-value based indices, maximum Tmax, minimum Tmin, and summer days have all shown increasing trends, whereas frost days and the diurnal temperature range have shown significant decreasing trends. Extreme cold events have obviously decreased in most parts of the eastern HKH, especially in Southwest China and the TP, whereas extreme warm events have generally increased over the whole HKH. The change in extreme cold events in the HKH has seemed more sensitive to elevation, with cold nights, cold days, and frost days obviously decreasing with elevation, but the change in extreme warm events has shown no detectable dependence on elevation.

Zhan et al. (2017) were the first to analyze the change in extreme precipitation events in the HKH overall over the last six decades. The authors applied a multi-source daily precipitation dataset (GLDP-V1.0) recently developed by CMA and found that the amount and days of light precipitation have tended to increase significantly in most parts of northern India and the northern TP during 1961−2012, but its intensity has generally decreased in the HKH and parts of northern India. In addition, they found the amount and frequency of moderate precipitation to have exhibited no significant trends in the HKH on a whole, the amount and frequency of intense precipitation events to have mostly increased significantly in the TP, but a heterogeneous change in other areas of the study region during 1961−2012. They observed the regional average annual 24-h, 3-day, and 5-day maximum precipitation to have exhibited significant upward trends, and a tendency for continuous rainy days to last significantly longer in most parts of the study region, whereas continuous dry days have shown no noticeable long-term trend.

Wu et al. (2017) projected future changes in mean temperature, precipitation, and four extreme climate indices (TXx, TNn, R95p, and RX5day) over the HKH based on the outputs from 21 Coupled Model Intercomparison Project Phase 5 (CMIP5) models under RCP4.5 and RCP8.5 scenarios. Their results showed a general increase in the mean temperature, TXx, and TNn, with the largest increases occurring in 2066−2095 under RCP8.5. The authors projected future precipitation to increase over most areas of the HKH, excepting the northwestern part, and precipitation extremes to intensify over the region. They also discussed the uncertainties associated with the projections. The uncertainties of R95p and RX5day precipitation projections seem to be greater following increases in greenhouse gas concentrations, for example, and the uncertainties of temperature in the TXx and TNn projections over the western HKH sub-region are greater than those for other sub-regions.

Sanjay et al. (2017) reported their climate change projection results for the HKH based on the Coordinated Regional Climate Downscaling Experiment (CORDEX) South Asia framework and the RCP4.5 and RCP8.5 scenarios for the near-future (2036−2065) and far-future (2066−2095) periods. The downscaled multi-RCM projection shows a seasonal mean warming of 5.4 °C during winter and 4.9 °C during the summer monsoon season by the end of 21st century under the RCP8.5 scenario for the hilly sub-region of the Karakoram and northwestern Himalayas. However, there is less agreement among these RCMs on the magnitude of the projected warming over the hilly sub-region of the central Himalayas. The downscaled multi-RCMs projections also show an intensification of summer monsoon precipitation of about 22% in the southeastern Himalayas and TP for the far-future period under the RCP8.5 scenario. There is greater uncertainty regarding the simulated changes in the summer monsoon and winter-season precipitation over the central Himalayas, Karakoram, and northwestern Himalayas. The authors consider improvements in the regional processes and feedback in the RCMs to be essential to reduce uncertainty and provide more reliable regional information suitable for future climate change impact assessments in the HKH.

To project changes in future extreme temperature and precipitation over the Koshi River Basin of the HKH, Rajbhandari et al. (2017) use the outputs of the Quantifying Uncertainties in Model Prediction simulations by the Hadley Centre Couple Model (HadCM3) based on the IPCC SRES A1B emission scenario. The authors show that, although the rainfall amount will probably not significantly change in the future, the frequency and intensity of extreme rainfall events, consecutive dry and wet days, and intense rainfall amounts will likely increase over the southern plains. Future extreme maximum and minimum temperatures are also projected to increase, with the minimum temperature increasing at a higher rate. Warm days will likely increase throughout the basin, especially in the high and trans-Himalayan area. Warm nights are also projected to increase, especially in the southern plains. A decrease is projected in the number of cold days and cold nights, indicating overall warming throughout the basin.

Overall, the studies reported here show a significant warming trend over the past century and recent decades over the HKH (Table 1). Based on different climate models, this warming trend is projected to continue in future. Although EDW has not been detected for mean temperature, this phenomenon seems to exist for cold climate events such as cold nights, cold days, and frost days, which have exhibited a more obvious decrease in frequency during recent decades at higher elevations. However, the reason for this is not well understood. Past changes in precipitation are more complicated. No coherent increase or decrease has been found for annual total precipitation change, despite the fact that the annual 24-h, 3-day, and 5-day maximum precipitation show significant increasing trends, and consecutive rainy days have also shown significant increases in most parts of the HKH.

Models generally produce long-term future trends similar to those observed in the past, with surface mean and extreme warm air temperatures continuing to rise and precipitation and intense rainfall also likely to increase under global warming. It is also possible that western regional disturbances will become more frequent, elevating the probability that winter snowfall in the Karakorum and western Himalayas will increase in frequency and amount.

Uncertainties exist in both observational studies and modeling projections. Long-term observational data is lacking in the high-altitude areas of the region, including the northwestern TP and Karakorum (Ren et al., 2017; Sun et al., 2017b; Zhan et al., 2017). There are also large inconsistencies and high inhomogeneity in the data. Significant systematic biases may be caused by the urbanization effect in the surface air temperature data series, particularly on the eastern TP (Zhang et al., 2010; Ren and Zhou, 2014) and probably in northern India and by the under-catch effect in the precipitation data on estimates of winter precipitation trends (Sun et al., 2013) in most areas, including the TP and southwestern China. Further examination and adjustment of the observational data are urgently needed.

The consensus regarding the projections based on climate models for the HKH is generally weak compared to that for other regions of Asia, although the multi-model projections generally agree on the direction of temperature changes. This is probably due to the highly complex topography and relatively coarse resolution of the global climate models used in these studies. Improvement in the climate models is essential to better represent the diversity and complexity of the HKH climate and to generate projections of future change with more confidence.

Despite existing uncertainties, the research results reported in this special issue will better our understanding of the complex interactions of the various components of the mountainous system, and also improve our evaluations of the potential impacts of climate change and variability on natural and human systems in important regions of the world. In view of the impact of climate change, for example, it is possible that the continuing warming in combination with other anthropogenic impacts such as increasing emissions and deposition of aerosols will accelerate the melting of mountainous glaciers in the HKH, especially in the southern and eastern areas of the region. Furthermore, the combination of the projected warming and increase in intense precipitation in the mid to high mountains will probably worsen the risk of flooding disasters in the lower reaches of the rivers.

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