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Observed changes in surface air temperature and precipitation in the Hindu Kush Himalayan region over the last 100-plus years

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Abstract

In this paper, we analyzed the long-term changes in temperature and precipitation in the Hindu Kush Himalayan (HKH) region based on climate datasets LSAT-V1.1 and CGP1.0 recently developed by the China Meteorological Administration. The analysis results show that during 1901−2014 the annual mean surface air temperature over the whole HKH has undergone a significant increasing trend. We determined the change rates in the mean temperature, mean maximum temperature, and mean minimum temperature to be 0.104 °C per decade, 0.077 °C per decade, and 0.176 °C per decade, respectively. Most parts of the HKH have experienced a warming trend, with the largest increase occurring on the Tibetan Plateau (TP) and south of Pakistan. The trend of precipitation for the whole HKH is characterized by a slight decrease during 1901−2014. During 1961−2013, however, the trend of the annual precipitation shows a statistically significant increase, with a rate of 5.28% per decade and has a more rapid increase since the mid-1980s. Most parts of northern India and the northern TP have experienced a strong increase in the number of precipitation days (daily rainfall ≥1 mm), whereas Southwest China and Myanmar have experienced a declining trend in precipitation days. Compared to the trends in precipitation days, the spatial pattern of trends in the precipitation intensity seems to be more closely related to the terrain, and the higher altitude areas have shown more significant upward trends in precipitation intensity during 1961−2013.

Keywords: Climate change; Temperature; Precipitation; Trend; Hindu Kush Himalayan; Tibetan Plateau

1. Introduction

The Hindu Kush Himalayan (HKH) region, which is sometimes referred to as the world's Third Pole, has a significant impact on Asian climate and even on global atmospheric circulation due to its great mountain systems and large area of permanent ice cover (Qiu, 2008; Yanai and Li, 1994; Yao et al., 2012a). In addition, the HKH region is also the source of ten major river systems, global biodiversity hotspots, and 330 important bird areas (Sharma et al., 2016).

Analyses on climate change have been conducted based on various datasets, including observations and reanalyzes, but most research has focused on small areas of the HKH region, for example, the transboundary Koshi basin, northwest

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Himalayas (NWH), Tibetan Plateau (TP), and Western Himalayas (WH) (Mann et al., 1999; Shrestha et al., 1999, 2010; Archer and Fowler, 2004; Bhutiyani et al., 2007; Shrestha, 2008; Palazzi et al., 2013; Kuang and Jiao, 2016; Sharma et al., 2016).

Although all studies focusing on TP, WH have reported significant warming during the 20th century to five decades, the warming rates vary greatly (Kang et al., 2010; You et al., 2013, 2016). Liu and Chen (2000) found the linear increasing rate over the entire TP was about 0.16 °C per decade during 1955–1996 for the annual mean temperature. Yan and Liu (2014) found warming trend of 0.32 °C per decade for 1961–2012, which is almost double the previous estimate. The warming observed in the TP has been more sensitive and has accelerated since the end of the last century (Kosaka and Xie, 2013; You et al., 2016). Also, a more asymmetric pattern of greater warming trends in the minimum temperature than in the maximum temperature has been observed in the TP (Liu et al., 2006, 2009; Duan and Wu, 2006). Significant warming of the winter and annual temperatures has also been observed over the Western Himalayas in the last century (Mann et al., 1999; Kothawale and Kumar, 2005; Bhutiyani et al., 2007). The temperature increase over the WH is also supported by the more rapid growth of tree rings in the high-altitude tree-ring chronologies of the region (Borgaonkar et al., 2009). The warming trends observed by the WH stations in winter over the last few decades were found varied greatly, although all stations with sufficiently long observational records show increasing trends (Dimri and Dash, 2012). The warming rate is reported to be more substantial in winter compared to other seasons in most parts of the HKH region (Bhutiyani et al., 2007; Shrestha et al., 2010).

In addition to the scant analyses of precipitation change in the HKH as a whole, the change rates and trends estimated by various research groups differ to some degree. With respect to Himalayan and northwest Himalayas precipitation, most studies have reported decreasing summer precipitation over the last six decades, but the reported winter precipitation trends differ, based on the use of the datasets, i.e., 0.05 mm d^{-1} per decade based on Climatic Research Unit (CRU) data and −0.04 mm d^{-1} per decade by Global Precipitation Climatology Center (GPCC) data, with both results exceeding the significance test (Palazzi et al., 2013). Annual and cold-season precipitation in the TP has increased over the past decades, and also the winter precipitation in the Indus basin, although there is no spatially coherent pattern of long-term precipitation change in this region (Ren et al., 2000, 2005, 2015; Archer and Fowler, 2004; Qin et al., 2005; You et al., 2015). The increase in annual precipitation in the north-eastern TP seems abnormal in relation to the tree-ring-based paleo-reconstruction of precipitation over the last 1000 years (Shao et al., 2010).

The climate change on the HKH has caused significant glacial retreat, snow melt, and permafrost degradation (Kang et al., 2010; Yao et al., 2012a,b), and has led to significant changes in the hydrology and water resources of Brahmaputra River, India River and other major rivers, and also some biodiversity hotspots (Immerzeel and Bierkens, 2012; Immerzeel et al., 2010; Kuang and Jiao, 2016; Yang et al., 2014), so there is growing concern regarding the climate change in Himalayan regions (Shrestha et al., 1999; Liu and Chen, 2000). A comprehensive analysis of climate change, especially temperature and precipitation change, is necessary for evidence-based decision-making to ensure the appropriateness and feasibility of measures taken to adapt to climate change and variability and to advance human well-being (Sharma et al., 2016). However, due to critical data gaps, as yet there have been no region-averaged surface air temperature or precipitation analyses of the past century and decades for the HKH as a whole, and the regional climate change rates of recent decades estimated by various research groups using different data sources differ to some degree. In this paper, using new climate datasets, we calculated the long-term temperature and precipitation changes in the HKH region as a whole and analyzed their spatial distributions to better understand climate change in this region and to provide more information for the modeling and analysis of regional climate change and its impact on natural and social systems.

2. Data and methods

The source for monthly mean temperature (Tmean), maximum temperature (Tmax), and minimum temperature (Tmin) is National Meteorological Information Center, China Meteorological Administration (NMIC, CMA), Global Land–Surface Air Temperature dataset (LSAT-V1.1) (Xu et al., 2014). The data in the CMA LSAT-V1.1 have been quality-controlled and homogenized. Data homogenization is important in long-term temperature change studies, because the inhomogeneity caused by station relocations and instrumentation can contribute to differing estimates of temperature change in a region. The data records begin in 1901. If there are six months in a given year without data, we did not include that year in the calculation. We selected for analysis only those stations with at least 15 years of records in the 1961–1990 base period, with the stipulation that station records contain at least 5 years of data during the first and last halves of the analysis period (1901–1960 and 1990–2014). Ultimately, we used 94 stations for the HKH temperature analysis, the distribution of which is shown in Fig. 1.

The source of the monthly and daily precipitation measurements is the CMA Global Precipitation dataset V1.0 (CGP1.0) (Yang et al., 2016). The monthly data in the CGP1.0 have been quality controlled and the record length is 114 years (1901–2013). The daily data have also been quality controlled but are not homogenized, and contain records for 53 years (1961–2013).

To investigate the precipitation change in 1901–2014, we selected stations with at least 10-year precipitation records in the 1961–1990 base period, at least 5 years in the 1901–1960 period, and at least 5 years in 1991–2014, for a total of 245 stations, as shown in Fig. 2. Except for India and Southwest China, the density of the station locations is not sufficient.

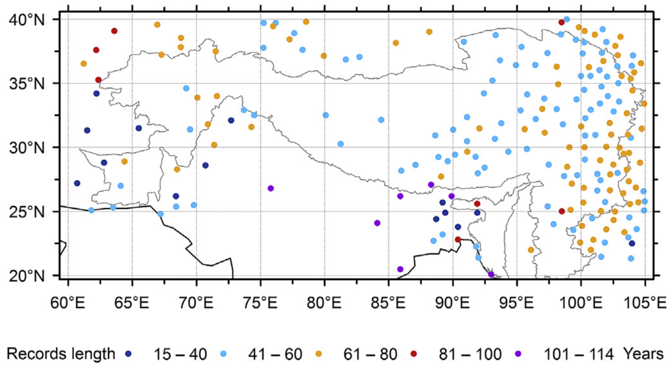

Fig. 1. Spatial distribution of stations and length of temperature records in the HKH (20°−40° N, 60°−105° E).

As there are huge discrepancies in the yearly precipitation records in the study region, we used precipitation standardized anomalies (PSA) to calculate the regional precipitation averages and to compare the change trends in different parts of the HKH. We used the precipitation percentage anomaly because it is sometimes a more useful indicator for comparing regional and temporal precipitation differences, and wet days (daily rainfall ≥1 mm) and simple daily intensity index (SDII, index of precipitation intensity, or the ratio of total precipitation to the number of wet days) were also applied in our analysis.

To reduce the biases caused by the uneven station density and the temporal variations in data coverage, we utilized the Climate Anomaly Method (CAM, Jones and Moberg, 2003). First, we assigned each station to a regular 5° × 5° latitude−longitude grid box, each of which contained at least one station. Then, we calculated the anomalies of the grid box temperature/precipitation indices, for example, by averaging the anomalies of the stations within grid boxes. Lastly, we calculated the HKH regional average anomalies by the area-weighted (using the cosines of the mid-grid latitude as weights) average of all the grid box anomalies.

As the reference period, we chose 1961−1990 mainly because of its better spatial record coverage. Using the least squares method, we determined the linear trends of the time series as the linear regression coefficients. We determined the significance of the linear trends using the Mann−Kendall-test method. In this assessment, a trend is considered to be statistically significant at the 5% ($p < 0.05$) level.

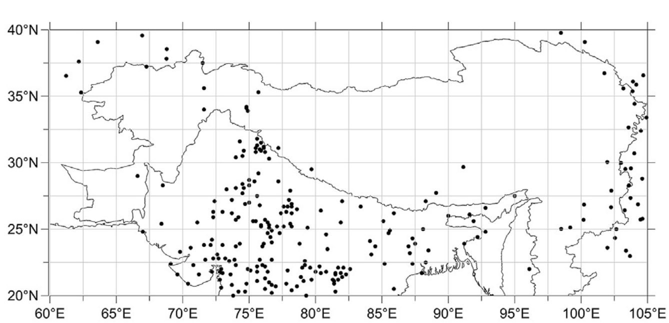

Fig. 2. Spatial distribution of stations recording precipitation in the HKH.

3. Past and current climate change in the HKH

3.1. Surface air temperature change

We found the surface air temperatures over 1901−2014 exhibiting a significant increase in the entire HKH. The annual mean temperature shows significant upward trends ($p < 0.05$), and the increase rates for Tmean, Tmax, and Tmin are 0.104, 0.077, and 0.176 °C per decade, respectively (Table 1). The diurnal temperature range (DTR) shows a significant negative trend of −0.101 °C per decade due to the much larger increase in the minimum temperature than in the maximum temperature in the region.

The regional average annual mean temperature series of the HKH also shows a large decadal to multi-decadal variability over the last 100-plus years. In terms of the Tmean change, we can observe three different stages (Fig. 3a). From 1901 to the early 1940s, most years show negative anomalies, and Tmean increases slightly. From the 1940s to the late 1970s, a relatively cold period in the Northern Hemisphere, the HKH temperature series shows a significant decreasing trend. After the 1970s, however, a dramatic warming appears in the HKH region. The decadal to multi-decadal variations of the warming and cooling episodes are generally consistent with previous studies of the TP and other areas of the HKH (Tang and Ren, 2005). In addition, the period 1998−2014 has witnessed the warmest years of the past 100 years, despite the fact that the annual mean warming trend in this period slowed, which is consistent with global and Northern Hemisphere observations (Trenberth et al., 2014). The warmest two years in 1901−2014 in the HKH region were 2007 and 2010.

The annual mean time series of Tmax and Tmin in the HKH region exhibit similar decadal to multi-decadal variations as those of Tmean (Fig. 3b). Prior to the 1960s, the annual mean Tmin anomalies are lower than those of Tmax, but are generally higher than those of Tmax afterward. The annual mean DTR shows relatively stable change prior to the 1940s, but declines significantly in the post-1940s period. After the 1960s, although the Tmax anomaly is obviously lower than that of the Tmin, it undergoes a similarly large increase as that of the Tmin. Because of the poor station coverage prior to the 1940s, the temperature anomaly time

Table 1
Annual mean surface temperature trends during 1901−2014 and 1951−2014 in the HKH region and the globe (Unit: °C per decade).

Region	Data source	Period	Tmax	Tmin	DTR	Tmean
HKH region	CMA	1901−2014	0.077	0.176	−0.101	0.104
		1951−2014	0.156	0.278	−0.123	0.195
Globe (lands)	CMA	1901−2014	0.100	0.142	−0.036	0.104
		1951−2014	0.186	0.238	−0.054	0.202
Globe	GHCN	1901−2014				0.084
(lands + oceans)		1951−2014				0.129

Note: All of the trends are statistically significant at the 0.05 confidence level. The trends of GHCN are from https://www.ncdc.noaa.gov/cag/time-series/global/globe/land_ocean/ytd/12/1880-2014.

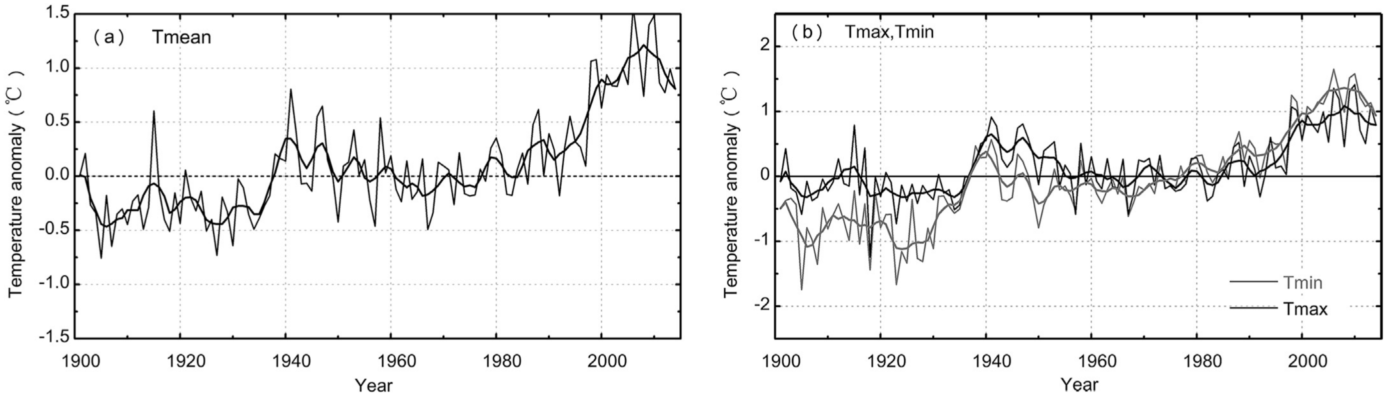

Fig. 3. Annual mean temperature anomaly series (°C) (relative to 1961–1990 mean) for (a) Tmean, (b) Tmax and Tmin for the HKH during 1901–2014.

series shows strong inter-annual fluctuations, indicating relatively large sampling uncertainty during this period.

The annual mean temperature trends in the HKH region show generally good agreement with those of the global land surface for different periods, with only very small differences (Table 1). During 1901–2014, the HKH region exhibited trends in Tmean similar to those of the global land surface. For 1951–2014, the trend of annual mean Tmax/Tmin in the HKH is lower/higher than the global trend. The decline in the annual mean DTR reflects a lower trend in the HKH region than that of global land.

These results differ somewhat from the research output regarding small regions. To compare our results with those of previous studies and also to determine the spatial distribution of temperature change, we calculated the annual mean temperature trends of each grid in the HKH (Fig. 4).

As shown in Fig. 4, climate warming is more obvious in the Tibetan Plateau, east HKH, and southern Pakistan and the adjoining Indian territory in 1901–2014. Overall, the majority of grids consistently show annual warming trends, but obviously different warming rates. The larger changes have occurred in the TP and south of Pakistan, with warming rates above 0.20 °C per decade. The warming rates seem to increase with increasing altitude, which is similar to the results reported from other analyses (Shrestha et al., 1999; Shrestha, 2008; Liu and Chen, 2000; Guo et al., 2016; Yan et al., 2016), and which support the claim that an altitude-dependent warming trend exists in the HKH. Northern India/Pakistan and the Sichuan Basin of China show the weakest warming trends, with annual warming rates below 0.10 °C per decade. Notably, there were fewer available data for India and Nepal for the centennial-scale analysis, and this may have resulted in a greater uncertainty in estimating the long-term temperature trend.

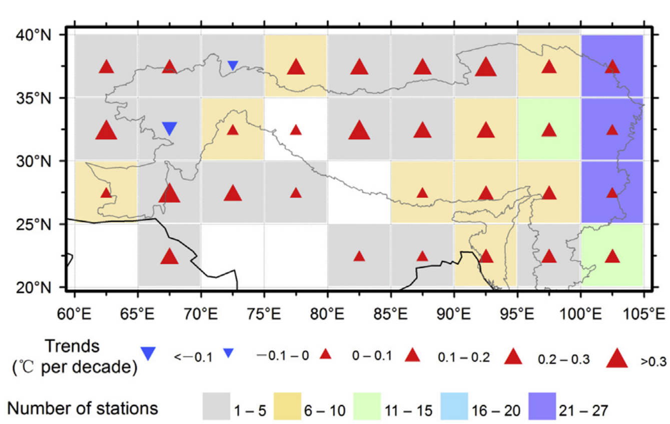

Fig. 4. Grid-averaged trends of annual mean temperature in the HKH in 1901–2014. The box colors indicate the station number and white grid boxes indicate missing data.

3.2. Precipitation change

The annual precipitation in HKH shows a long-term negative trend over 1901–2014 (Fig. 5). The regional average precipitation standardized anomalies (PSAs) fluctuate with more positive values during 1930–1960, more negative ones after 2000, and an overall negative trend in 1901–2014 (Fig. 5a). We did not calculate any trends for the northwestern TP due to the lack of precipitation records prior to 1951. The precipitation standardized anomalies and percentage anomalies decrease slightly in Southwest China and most parts of northern India, but increase in the northeastern part of West Asia (Fig. 5c and d). However, all the trends are not statistically significant at the 0.05 level. The reduction in annual precipitation in northern India and Southwest China seems consistent with the reported weakening of Indian summer monsoon over the past century (Ding and Ren, 2008).

In contrast, the annual precipitation over 1961–2013 has increased in the HKH region (Fig. 6). During this period, station coverage in the TP has improved significantly and this is the reason for the difference of trends between Figs. 5 and 6. The regional average precipitation standardized anomalies and percentage anomalies were mostly positive in the 1950s (Fig. 5), fluctuated from the 1960s to the 1980s, and obviously increased after 1990, particularly percentage anomalies (Fig. 6a and b). The annual precipitation percentage anomalies exhibit an obvious upward trend during 1961–2013, with the highest value in 2007. Overall, the regional average precipitation percentage anomaly has increased at a rate of 5.28% per decade, which is significant at the 0.01 level. However, the annual precipitation standardized anomaly has exhibited an insignificant upward trend, despite the fact that it has increased

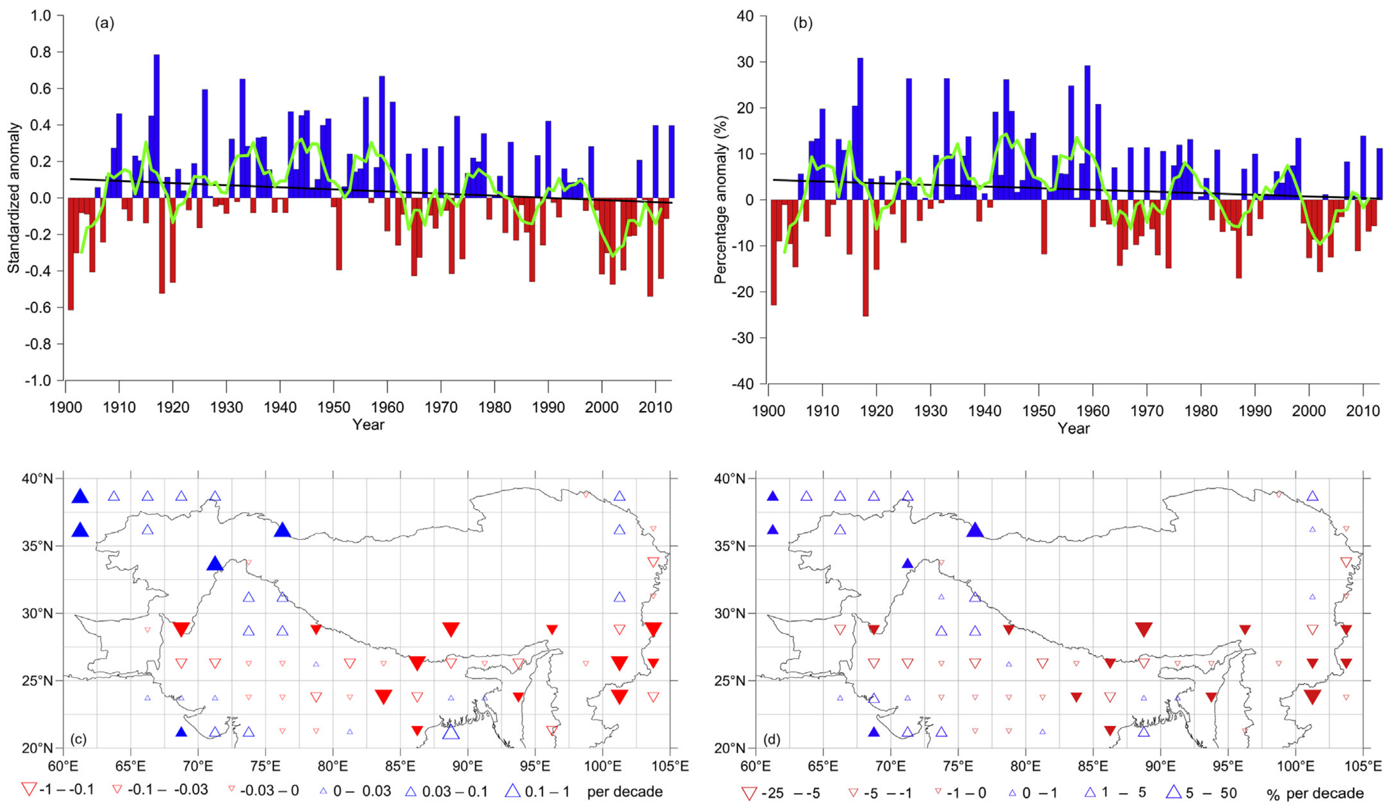

Fig. 5. Regional average annual (a) precipitation standardized anomalies (PSA), and (b) precipitation percentage anomaly (PPA) during 1901−2014 in the HKH (with green line denoting five-year moving average and black line the linear trend); spatial distribution of linear trends in (c) PSA, and (d) PPA in 1901−2014.

more rapidly since the mid-1980s. As noted above, our analysis result for precipitation change in the HKH region is generally supported by previous studies, especially those of the TP region and the Indus basin (Archer and Fowler, 2004; Ren et al., 2015; You et al., 2015).

The anomaly of wet days experienced a slight and insignificant decline over 1961−2013 (Fig. 6c). Prior to 1990, the change in the regional average wet day anomaly was similar with that of precipitation standardized anomaly. However, except the values in 2013 and 2009, wet day anomaly seemed not to change after 1990 in the HKH region as a whole. The wet day anomaly shows a slight decreasing trend of −0.629 d per decade, which does not pass the 0.05 confidence test. This result differs from those of most studies conducted with respect to mainland China, which report a significant decrease in wet days (Ren et al., 2015).

The region-averaged annual mean precipitation intensity (SDII) anomaly decreased from 1961 to 2013, with relatively larger negative anomalies after 1998. However, the SDII anomaly exhibits an abnormally high value in the early 1990s, although it drops once again after 1994. The SDII anomaly exhibits a slight downward trend of −0.075 mm d^{-1} per decade, which is not significant at the 0.05 level.

It is obvious that the annual precipitation experienced an obvious shift after 1990 in the HKH region. Although the wet day anomaly fluctuated and had a weak downward trend, the PPA saw a significant increase during the recent two decades-plus.

Fig. 7 shows the spatial distribution of the linear trends in annual precipitation percentage anomaly, wet day anomaly, and precipitation intensity (SDII) anomaly during 1961−2013. The positive percentage anomaly trends are statistically significant in some of the grids in the TP region and a few grids of India, but the annual percentage anomaly generally decreases in Southwest China, the northeastern part of India, and the north-eastern most part of the HKH region. This result is generally consistent with studies conducted in sub-regions, including those for the TP, which also reported increased precipitation and non-uniform precipitation change across the HKH (Palazzi et al., 2013; You et al., 2015; Kuang and Jiao, 2016).

The wet days exhibit a strong increase in most parts of India and the northern TP, but a strong decline in Southwest China and Myanmar. Wet day and precipitation intensity anomalies exhibit approximately opposite trends during the analysis period, especially in southern and southeastern HKH. In most parts of India and the northern TP, for example, wet days obviously increases, but the precipitation intensity decreases significantly, whereas Southwest China and Myanmar experienced a significant decline in wet day anomalies, but a significant increase in precipitation intensity anomaly. The temporal characteristics of the precipitation variation seem to have entered a mode of greater extremes in south-eastern HKH.

A more significant increase in the annual mean daily precipitation intensity over the past decades seems to have

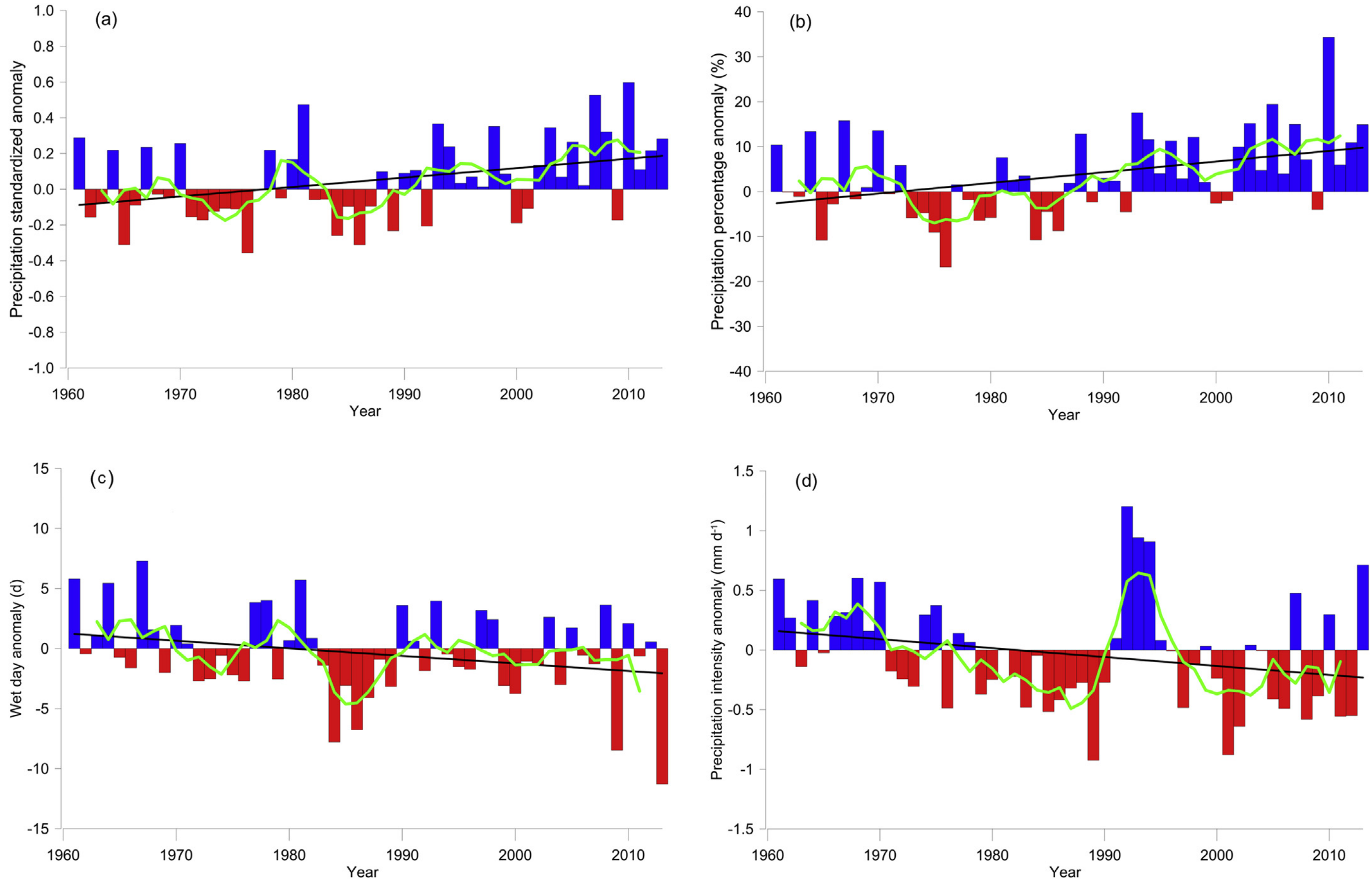

Fig. 6. Regional average annual (a) precipitation standardized anomalies (PSA), (b) precipitation percentage anomaly (PPA), (c) wet-day anomalies (WDA), and (d) precipitation intensity (SDII) anomaly (PISA) over 1961–2013 in the HKH (Green line is the five-year moving average, and black line is the linear trend).

occurred in higher altitude areas, including the TP. Compared to wet day anomaly trends, the spatial distribution of trends in precipitation intensity (SDII) anomaly seems to be more closely related to the terrain rather than longitude. The annual SDII anomaly significantly increased in most parts of the TP and the Yunnan–Guizhou Plateau, but significantly decreased in northern India and other areas south of the Himalayan Mountains. It is unclear what has caused this spatial pattern.

4. Discussion

4.1. Elevation-dependent warming in the HKH

The phenomenon of elevation-dependent warming (EDW) in the HKH, and in the TP and its surrounding regions in particular, has been reported by many research groups, but arguments persist regarding the association of warming trends with elevations (Duan and Xiao, 2015; Guo et al., 2016; Pepin et al., 2015; Yan and Liu, 2014; Yan et al., 2016; You et al., 2016).

Liu and Chen (2000) reported a more pronounced warming at high elevations compared with that of surrounding regions in the TP, which has since been confirmed in numerical simulations, and this tendency may continue in future climate change scenarios (Chen et al., 2003; Liu et al., 2009). You et al. (2008) failed to identify an elevation dependency in the trends of temperature extremes in the eastern and central TP. In our study results, EDW in the HKH region seems clear, as shown in Fig. 4. Grids with an annual mean warming greater than 0.2 °C per decade for 1901–2014 are mostly distributed in the TP, but they also occur in low-lying southern Pakistan and western India. The slowest warming and even cooling is seen in eastern Afghanistan and the Karakorum Mountains. These varied conclusions are probably due to the differing datasets, periods of analysis, and lowland stations used for comparison (Kang et al., 2010).

The feedback of a diminishing cryosphere that is more sensitive to greenhouse gas emissions is perhaps the reason for the different temperature changes in high-elevation regions (Yan et al., 2016). But the exact driving mechanisms responsible for EDW remain unclear and require further investigation to verify its presence in the HKH or the TP.

4.2. Limitations and gaps in observation and research

Major uncertainty arises from the systematic bias caused by the urbanization effect on surface air temperature observations in some areas, as well as from the big data gaps in the TP, northern India, Pakistan, and Afghanistan, especially in the early years.

The sparseness of observational data is the major source of uncertainty regarding the estimates of long-term climate

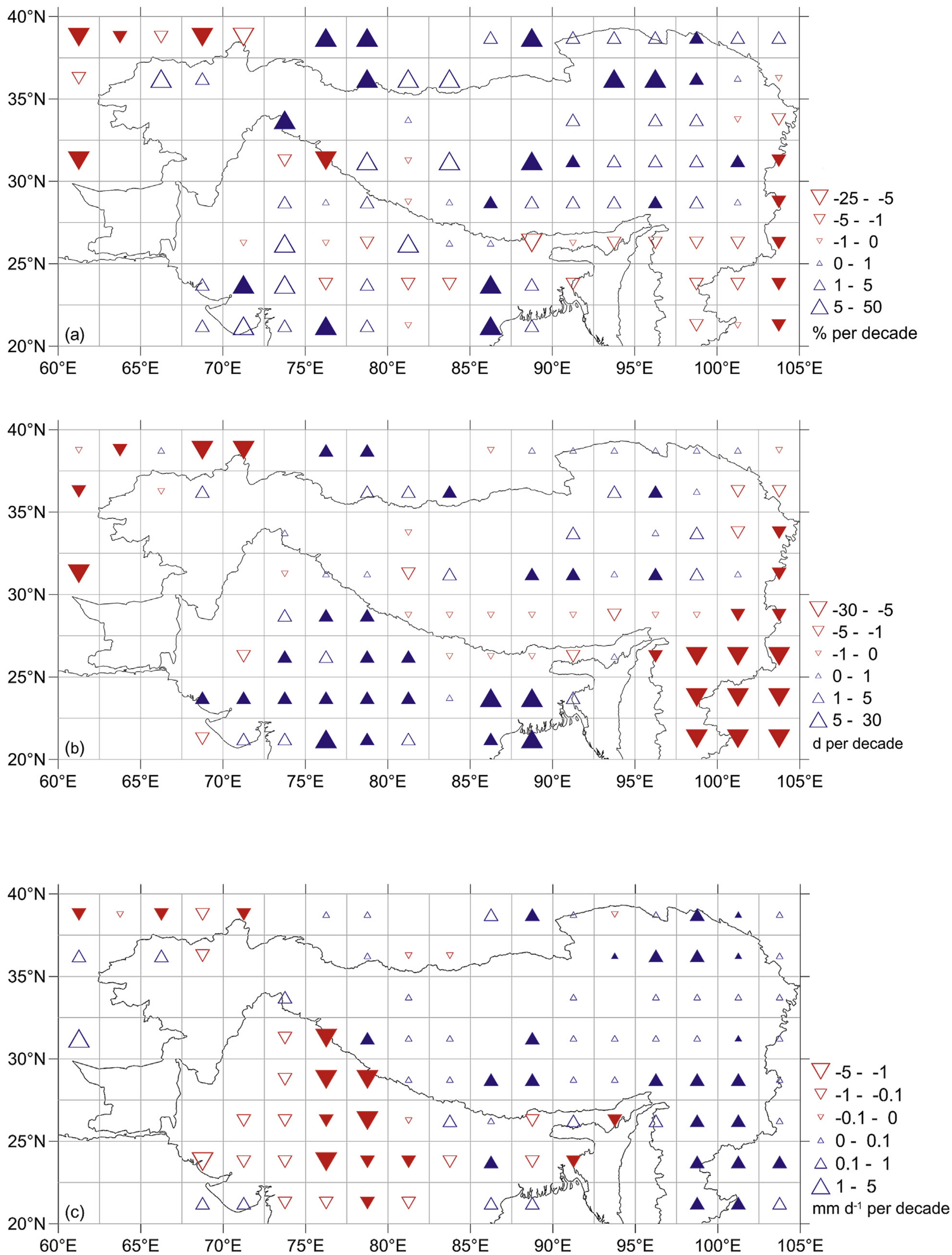

Fig. 7. Trends in annual (a) precipitation percentage anomaly (PPA), (b) wet day anomaly (WDA), and (c) precipitation intensity anomaly (PISA) over 1961−2013 in the HKH. Filled symbols represent statistically significant trends at the 0.05 confidence level.

trends in the HKH. The inhomogeneities in the CMA global land surface air temperature data set have been checked and partially adjusted before the construction of the temperature anomaly time series for varied periods (Xu et al., 2014). However, the systematic bias in the temperature data series due to urbanization has not yet been evaluated or adjusted. According to previous studies conducted in mainland China, urbanization effects on the regional average temperature series are relatively large and highly significant (Ren and Zhou, 2014; Ren et al., 2005; Wang and Ge, 2012). For the TP, the contribution of urbanization to the long-term annual mean temperature trend is greater than 23% (Ren et al., 2015), so this is not a bias that can be omitted in the analysis of long-term temperature change. If the percentage is applicable to the whole HKH and over longer period, the increase rate of the annual mean temperature in the region in 1901–2014 would be less than 0.08 °C per decade, albeit still statistically significant.

5. Conclusions

For 1901–2014, annual mean temperature shows significant increasing trends, with a mean temperature rate of 0.104 °C per decade, a mean maximum temperature rate of 0.077 °C per decade, and a mean minimum temperature rate of 0.176 °C per decade. The regional average annual mean temperature series shows obvious decadal to multi-decadal stage characteristics. The first stage is from 1901 to 1940, during which most years showed negative anomalies, and the time series exhibited relatively stable change. From the 1940s to the late 1970s, the temperature series showed some decrease trends, especially in the Tmax series. After the 1970s, dramatic warming trends appear in the temperatures of the HKH. Tmin experienced the most rapid increase, followed by Tmean, with Tmax exhibiting the slowest warming trend. The spatial pattern of temperature change reveal that most parts of the HKH experienced warming trends during 1901–2014. The largest increase occurred in the TP and south of Pakistan.

The long-term precipitation trend of the whole HKH is a slight decrease over 1901–2014. The precipitation standardized anomaly and percentage anomaly decreased slightly in Southwest China and most parts of northern India, but increased in the northeastern part of West Asia. However, these trends are small and not statistically significant at the 0.05 level. During 1961–2013, the regional average precipitation percentage anomaly shows statistically significant increase at a rate of 5.28% per decade and the annual precipitation standardized anomaly has increased rapidly since the mid-1980s, but this upward trend is not statistically significant. Both the wet day anomaly and precipitation intensity (SDII) anomaly show decreasing trends during 1961–2013. With respect to the spatial distribution, the TP has experienced an increase in all three precipitation indicators of wet day anomaly, percentage anomaly and SDII anomaly, whereas northern India has exhibited an increase in percentage anomaly and SDII anomaly but a decrease in wet day anomaly over 1961–2013. The temporal characteristics of the precipitation variation seem to have entered a mode of greater extremes.

There are big observational data gaps, especially in the early years, and urbanization-induced bias is the major source of research uncertainty in the HKH. Data coverage is improving, but time must pass to obtain sufficient records for analyzing past climate change. Further investigation is also required regarding the urbanization effect on surface observations, especially the surface air temperature records of urban stations, the EDW, and its driving mechanisms.

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