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Changes in extreme precipitation events over the Hindu Kush Himalayan region during 1961−2012

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Abstract

Based on a new multi-source dataset (GLDP-V1.0) recently developed in China Meteorological Administration, we employed precipitation indices including percentile-based indices of light (below the 50th percentile), moderate (between the 50th and 90th percentile), and intense (above the 90th percentile) precipitation, maximum 1-day, 3-day, and 5-day precipitation amounts (RX1DAY, RX3DAY, and RX5DAY, respectively), and consecutive wet and dry days (CWDs and CDDs) to analyze variations in extreme precipitation events in the Hindu Kush Himalayan (HKH) during 1961−2012. The main results are presented as follows. Firstly, there was a significant increase in the amount of light and moderate precipitation and number of associated days over various parts of India and northern Tibetan Plateau during 1961−2012; but the intensity of light precipitation decreased significantly in the Hindu Kush and central India, and the regional average intensity also decreased. Secondly, the amount and frequency of intense precipitation mostly increased significantly on the Tibetan Plateau, but there was a heterogeneous change over the remainder of the HKH, and regional average annual intense precipitation amount and frequency significantly increased over the HKH during 1961−2012. Thirdly, regional average RX1DAY, RX3DAY, and RX5DAY all showed significant upward trends during 1961−2012, and there was a significant increased tendency of consecutive wet-days in most parts of the study region; however, trends of consecutive dry-days were mostly opposite to those of consecutive wet-days, with regional averaged consecutive dry-days showing no noticeable trend.

Keywords: Climate change; Trend; Extreme precipitation events; HKH region; Tibetan Plateau

1. Introduction

The Hindu Kush Himalaya (HKH) region, as defined by Sharma et al. (2016), comprises many of the world's most extensive river basins and highest mountains (and one of the greatest mountain systems). With the exception of the North and South Poles, the HKH region contains the largest area of

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permanent ice cover worldwide, and as such is often referred to as the Third Pole of the Earth, and it provides ecosystem services sustaining the livelihoods of an enormous population. The HKH is characterized by extreme topographic and climate heterogeneity, where the steep mountains force vapor uplift and block moisture transport, thus producing strong horizontal and vertical gradients in precipitation (Sharma et al., 2016; Yanai and Li, 1994; Qiu, 2008; Yao et al., 2012); as a result, the distribution of water resources is extremely uneven, and both floods and droughts are common. This effect makes the HKH susceptible to changes in climatic conditions, particularly to changes in extreme precipitation. Understanding decadal changes in extreme precipitation is therefore significant for local and regional hydrology, agriculture, ecology, industry, and hydroelectric power generation, all of which rely on the timely and sufficient delivery of water in major river systems.

Previous studies have indicated that there has been a slight increase in precipitation on the Tibetan Plateau (TP) (You et al., 2015) since the 1960s, although the increase has not been as pronounced as that of temperature. This result is part of a broader climatic moistening trend that has been observed in western China, including the TP and Northwest China (Ren et al., 2000, 2005, 2015; Qin et al., 2005; You et al., 2015). Increasing trends in winter precipitation have also been reported over a few stations in the Indus basin since the post-1960s (Fowler et al., 2005), although no spatially coherent pattern of long-term change in precipitation has yet been detected over the region (Fricke and Höffken, 1999). For example, Shrestha et al. (2016) found that changes of extreme precipitation indices are different in the mountains than on the Indo-Gangetic plains, although their results were not statistically significant. Palazzi et al. (2013) summarized trends in precipitation in the HKH region and reported a generally decreasing trend in the Himalayas during summer over previous decades, but found no statistically significant trends during wintertime.

However, other studies have determined a significant change in recent extreme precipitation events in some areas of the HKH. For example, a number of studies have reported that western China (including the TP) has experienced a significant change in extreme precipitation events over the past decades (Du and Ma, 2004; Ren et al., 2012; You et al., 2015); such results are consistent with an increase in annual precipitation total and precipitation intensity but a decrease in wet days during the same period (Ren et al., 2015). Some stations over the Karakoram regions have also recorded an obvious increase in the number of wet days and extreme precipitation events during the past few decades (Klein Tank et al., 2006; Choi et al., 2009. In addition, a growing trend in extreme precipitation in contiguous areas (from the northwestern Himalayas in Kashmir to the Deccan Plateau in India) was determined during 1910–2000 (Sen Roy and Balling, 2004) and over central India during the monsoon seasons from 1951 to 2000 (Goswami et al., 2006).

However, studies of extremes in the HKH have certain limitations. For example, previous research based on station observation data has usually focused on changes in extreme precipitation in one country or in one region of the HKH. Therefore, a systematic analysis of spatial and temporal characteristics of long-term variations in extreme precipitation for the entire HKH region is lacking. The gridded precipitation products based on remote sensing data, which are frequently used in global or Northern Hemisphere studies, are often not capable of capturing large and abrupt precipitation variations over short distances, due to the coarse resolution and orographic effects in high-altitude areas (Dahri et al., 2016).

In this paper, the HKH is defined as a rectangular region with a boundary of 60–105°E and 20–40°N that includes the HKH high mountains and adjacent plain areas. Extreme precipitation is analyzed using a new multi-source dataset based on station data obtained in the HKH from 1961 to 2012, with a focus on long-term variations in extreme precipitation within the region.

2. Data and methods

The China Meteorological Administration (CMA) Global Land Daily Precipitation dataset V1.0 (CMA GLDP-V1.0) is the source of daily precipitation measurements used in this current analysis. Data have been subjected to quality control and records span a period of 65 years (1951–2015). However, many stations lack data both prior to 1960 and after 2013 in the HKH region; therefore, the period 1961–2012 is used in this analysis. In addition, as the spatial coverage of records was improved after the 1960s, the period 1961–1990 is selected as the reference period (Fig. 1a). Given that precipitation amounts below 1 mm can introduce uncertainties in estimating the annual number of wet-day biases (Zhang et al., 2011), in this study wet-days are considered to be days on which there was no less than 1 mm of rainfall, and PRCPTOT (total precipitation) is the total of all the daily precipitation on wet days. The SDII (simple daily intensity index), or precipitation intensity, is defined as PRCPTOT divided by the number of wet-days. Consecutive wet-days (CWDs) and consecutive dry-days (CDDs) are frequently used to detect flooding and drought events, and are defined as the maximum number of consecutive days when precipitation ≥ 1 mm or < 1 mm. The maximum 1-day, 3-day, and 5-day precipitation amounts (RX1DAY, RX3DAY, and RX5DAY, respectively) are the maximum 1-day or maximum consecutive 3-day or 5-day precipitation in a year.

If any station in the HKH has a year in which there are less than half-valid daily precipitation data for one or more months, this year is flagged as missing, and the data in the year are not used in the subsequent calculation process. To enable use of the optimum spatial density of stations in the major study region, a certain standard is employed in station selection, as follows: stations selected should have at least 5-year precipitation records during the base period 1961–1990, and at least 10 years in the total period 1961–2012. To reduce uncertainties in extreme precipitation analysis, stations with less than 50 wet-days during the base period are totally eliminated from analysis. A final total of 1122 stations and

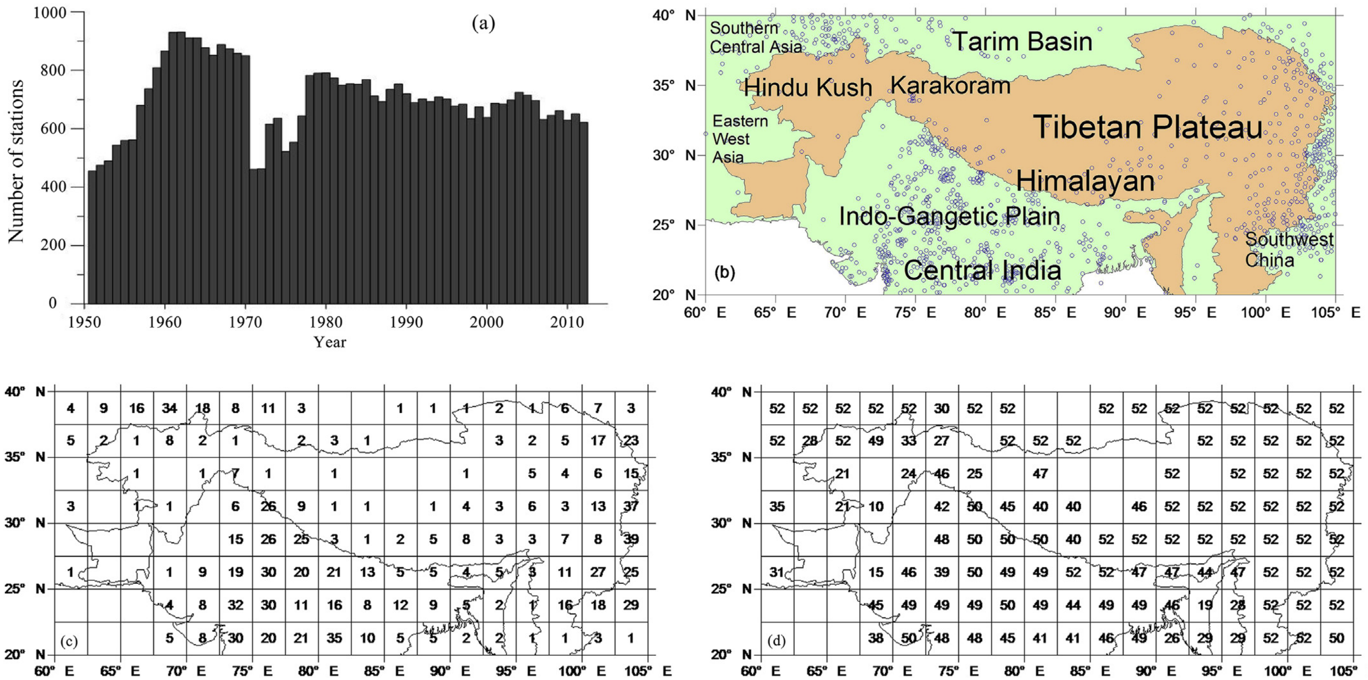

Fig. 1. (a) Number of stations during 1951−2015; and (b) spatial distribution of precipitation stations in the Hindu Kush Himalayan (HKH) region (20−40°N, 60−105°E). Sand color areas indicate HKH high mountains (including the Tibetan Plateau) and light green areas are plains (including southern Central Asia, eastern West Asia, Tarim Basin, Indo-Gangetic Plain, Central India, and Southwest China). (c) Number of stations in every grid; (d) number of years with valid records in every grid.

therefore used, as shown in Fig. 1b, and these stations are uniformly and densely distributed throughout India, the southern part of Central Asian countries, and Southwest China, but they are not so densely distributed in Afghanistan, Bangladesh, Bhutan, the TP, Myanmar, and Pakistan, where data coverage is relatively poor. In addition, station density is lower in the high attitude area of the HKH (sand color area in Fig. 1b) than on the plain.

The study region is huge and there is a wide discrepancy in the distribution of precipitation. Therefore, the amount of precipitation in one area has a different implication to the same amount of precipitation in another area. For example, a day with 20 mm of precipitation in New Delhi may be a common occurrence, but the same amount precipitation in Khotan (near the Taklimakan desert) could be a rare occurrence and may not be experienced again for several decades. Therefore, to solve this problem, relative threshold values are used to define the extreme precipitation indices in the assessment report. The gamma distribution is most frequently used to characterize the distribution of daily precipitation (Groisman et al., 1999), so that weaker amounts of precipitation can occupy a greater number of percentile ranges for all daily precipitation in the division of extreme precipitation events. A three-grade system is thus applied in this analysis, with a light precipitation day defined as daily precipitation below the 50th percentile value of all wet-days in the reference period, a moderate precipitation is daily precipitation between the 50th and 90th percentile, and an intense precipitation is daily precipitation above the 90th percentile. The precipitation amounts of each category are the accumulated precipitation, and the precipitation intensity is the precipitation amount divided by precipitation days.

As there are huge discrepancies in the yearly precipitation records throughout the study region, a change in precipitation or its anomaly for every category in a desert area could be erased when calculating regional averages. Therefore, a percentage of anomalies (PA) is used to compute changing trends in all precipitation indices within different parts of the HKH, to enable a comparison of trends in different areas. However, when computing the regional average it is possible to magnify the amount of precipitation in extremely dry areas. For example, if one station records only 0.1 mm of precipitation per year during the base period, the positive anomaly will be

Table 1
Linear trends of precipitation indicators of each category for 1961−2012 in the HKH.

Indicator	Light	Moderate	Intense	Total
PRCPTOT (PA) (% per decade)	**2.61****	1.84	**6.16****	**3.53****
Wet-days (PA) (% per decade)	**2.84****	**1.94***	**5.15****	**2.69****
SDII (PA) (% per decade)	**−0.46****	−0.27	**1.32***	0.33
PRCPTOT (NA) (per decade)	0.04	0.03	**0.09****	**0.08****
Wet-days (NA) (per decade)	**0.04***	0.02	**0.07****	**0.05***
SDII (NA) (per decade)	**−0.05****	**−0.04****	0.02	**0.05****
RX1DAY (PA) (% per decade)				**2.14****
RX3DAY (PA) (% per decade)				**2.26****
RX5DAY (PA) (% per decade)				**2.34****
CWDs (PA) (% per decade)				**1.41***
CDDs (PA) (% per decade)				−0.53

Note: * and ** denote statistically significant at the 0.05 and 0.01 confidence level, respectively. PA is for percentage anomaly and NA is for normalized anomaly.

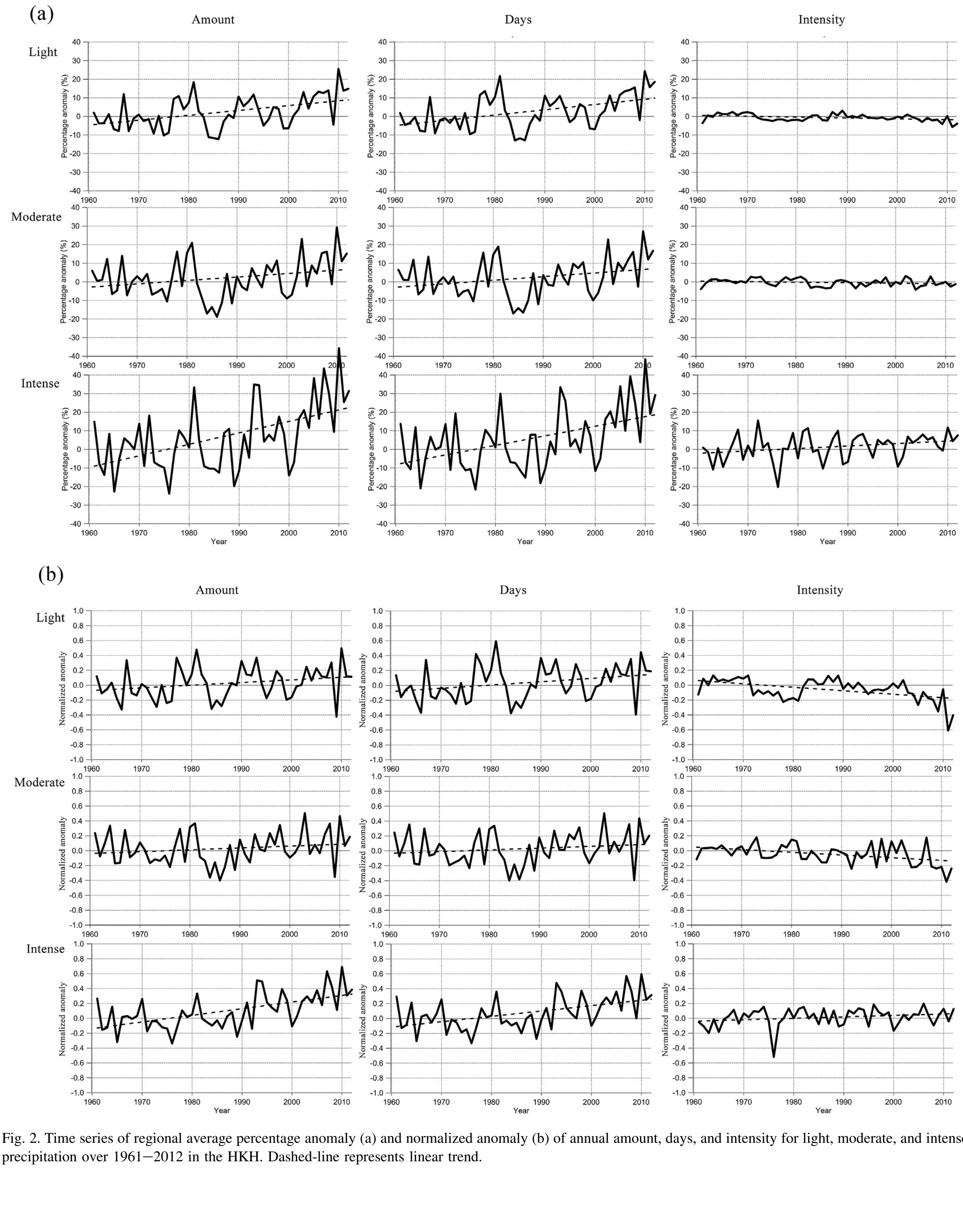

Fig. 2. Time series of regional average percentage anomaly (a) and normalized anomaly (b) of annual amount, days, and intensity for light, moderate, and intense precipitation over 1961–2012 in the HKH. Dashed-line represents linear trend.

900% when the total rainfall in one year reaches 1 mm. Therefore, as normalized anomalies (NA) are considered a better indicator when researching regional average temporal changes, NAs are also used in this study to calculate regional averages. Furthermore, several precipitation indices for extreme climate events referenced by ETCCDMI (Zhang et al., 2011; You et al., 2008) are used in this study, and the definitions of indices are found in Table 1.

The selected stations may have a maximum number of 42 missing years (80%) of the total period, and thus they can not to be used directly in analyses of regional average and change trends. The uneven spatial data coverage also cause problem if the regional values are obtained by directly averaging station data. To reduce the biases caused by station data, they were conversed to grid data and an area-weighted regional average method (Jones and Moberg, 2003) are employed. Firstly, each station in the HKH rectangular region is assigned to a regular 2.5° by 2.5° latitude−longitude grid box. The grid box values of annual precipitation indices are then calculated by averaging the stations in grid boxes that have at least one station. Grid boxes without any valid station values in one year are marked as blank. Finally, HKH regional average values are calculated by the area-weighted (using the cosines of the mid-grid latitude as weights) average of all grid box values.

Fig. 1c shows the number of stations used within every grid box. Blank grid boxes are those without valid station values in every year. Several grid boxes on the TP, and most grid boxes in Afghanistan and Pakistan, have no stations; there are less than five stations in other grid boxes in these areas. Regions with the best coverage of stations and grid boxes are India, the Chinese mainland east of 95°E, and southern Central Asia; most of the boxes in these regions contain more than five stations. Fig. 1d shows years that have valid records in every grid box; records mostly cover more than 30 years (more than 60% records) except for several boxes in Afghanistan, Pakistan, and Myanmar, indicating that the grid values of the whole study region have relatively good data coverage. Grid boxes with records covering no more than 30 years are excluded in trend analyses, but are used in the computing process for regional average time series. In summary, daily precipitation data used in this paper cover most areas of the HKH, except Afghanistan, Pakistan, and Myanmar; all other areas have a relatively sufficient temporal coverage of valid precipitation records.

The linear trends of the precipitation indices series are calculated using least squares method. The significance of linear trends is judged using the 2-tailed simple-test method. In this assessment, a trend is considered statistically significant if significant at the 5% ($p < 0.05$) level.

3. Changes in extreme precipitation

Both the amount and frequency of light and intense precipitation experienced remarkable changes over 1961−2012. Fig. 2 shows the regional average PA and NA of annual amount, days, and intensity for light, moderate, and intense precipitation over the period in the HKH region, and Table 1 shows linear trends of those, and test results of the significance. The remarkable increase in the amount and days of intense precipitation and the significant decline in the intensity of light precipitation are clearly observed in Fig. 2 and Table 1, but there is no obvious change in the amount of moderate precipitation over the assessment period. The PA and NA of the amount of light precipitation, moderate precipitation days, and intensity of intense precipitation all show significant trends; however, although their associated trends in PA

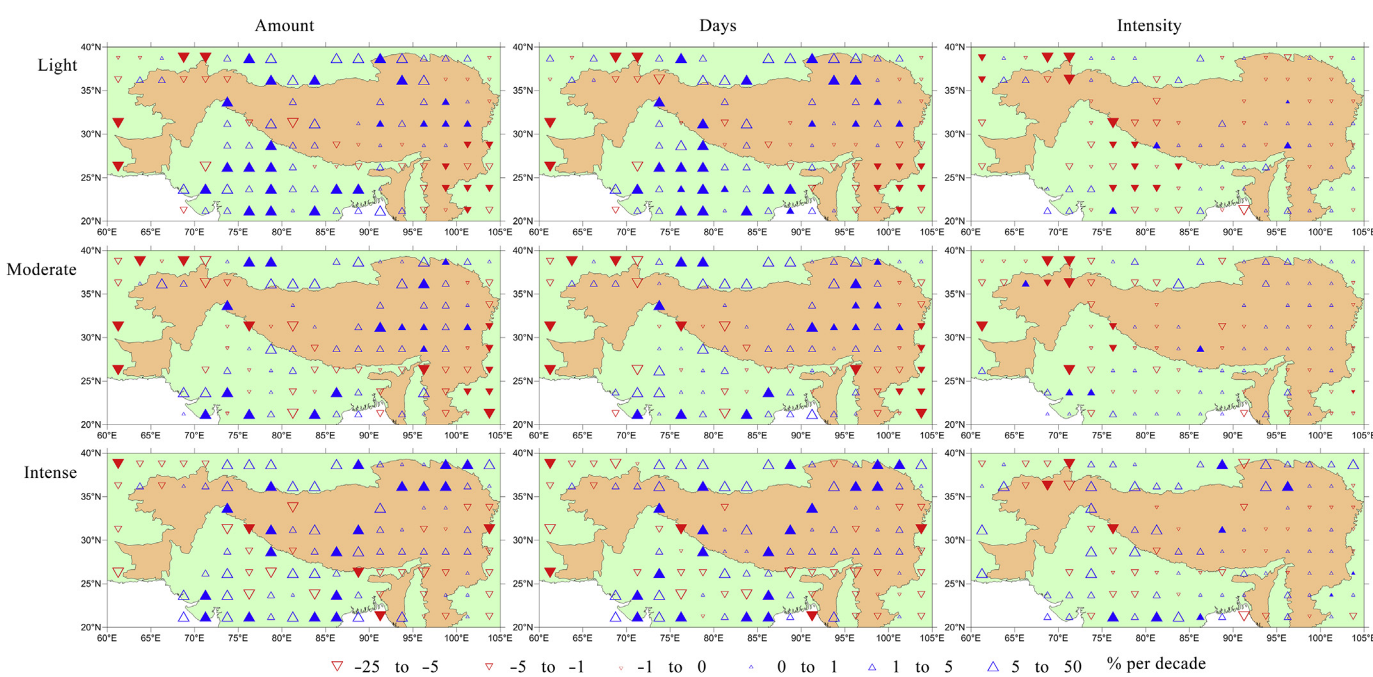

Fig. 3. Change trends (% per decade) in percentage anomaly of precipitation amount, precipitation days, and precipitation intensity for light, moderate, and intense precipitation over 1961−2012 in HKH. Symbols that are filled-in represent statistically significant trends at the 0.05 confidence level.

are statistically significant, the trends in NA are not. However, there are slight decreases in the PA of moderate precipitation intensity and the NA shows a significant decrease. In summary, regional averages of PA and NA both show the same upward or downward trends, but the trends have different significant levels (Table 1). In addition, after the year 2000, the PAs of every precipitation indicator all show relatively more remarkably positive values than the positive NAs.

Regional average annual amounts and days of light precipitation increased over 1961−2012, and their PA greatly increased after 2000 (Fig. 2). The PA change-rate of light precipitation amounts and days was 2.61% per decade and 2.84% per decade, respectively, which is statistically significant at 0.01. However, there was a decrease in the intensity of light precipitation in 1961−2012 (Table 1). The changing pattern of regional average moderate precipitation is similar to that of light precipitation, but less significant.

The regional average amount, frequency, and intensity of intense precipitation all increased over 1961−2012, particularly after 1990. Linear trends for the PA of them are 6.16, 5.15, and 1.32% per decade, respectively, which pass the 0.05 significance level (Table 1). However, increasing trends of NA are not so remarkable after the year 1990 (Fig. 2). The increasing trend of the intensity for NA is not significant at the 0.05 confidence level (Table 1). Nevertheless, the increasing frequency and intensity of intense precipitation in the HKH is

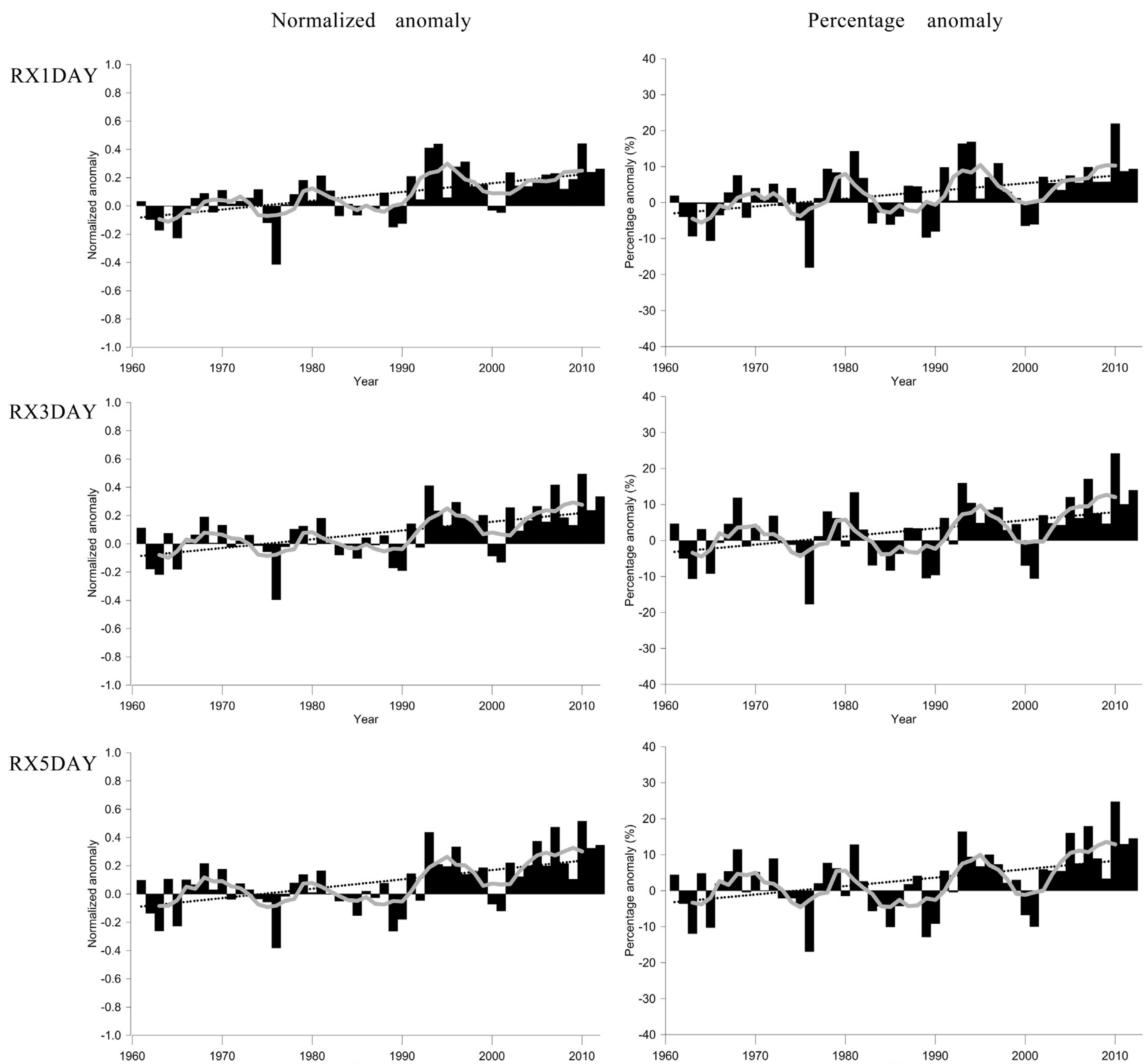

Fig. 4. Regional average normalized anomaly and percentage anomaly for RX1DAY, RX3DAY, and RX5DAY over 1961−2012 in the HKH. Gray line represents 5-year moving average and dotted line shows linear trend.

approximately consistent with that found in other mid-to high latitude regions (Sen Roy and Balling, 2004; Du and Ma, 2004; Ren et al., 2012; You et al., 2015).

Fig. 3 shows the spatial distribution of linear trends of precipitation indices for every grid box in the HKH. The annual light precipitation increases significantly in most parts of India, on the northern TP, and the southern Tarim Basin; however, there is a significant downward trend in Southwest China, and no considerable change is noted northeast of West Asia. The number of light precipitation days also increases significantly in most parts of India and northwestern TP, but a significantly reduction is seen in the southeastern part of the TP and Southwest China. The intensity of light precipitation decreases in almost every grid west of 85°E, except in the Tarim Basin, and it decreases significantly in the north of Hindu Kush and Central India.

The amount and frequency of moderate precipitation mostly increase in the TP, the Tarim Basin, and the Indian area south of 25°N, with a particularly significant increase in many TP areas east of 90°E. However, there is a significant decrease in the amount and frequency of moderate precipitation in Southwest China, northern Southeast Asia, and the northern Hindu Kush ($p < 0.05$). Nevertheless, the change rate in the intensity of moderate precipitation in the HKH is relatively small, with most of the absolute values less than 1% per decade.

The spatial patterns of linear trends in the amount and days of intense precipitation are similar; and they mostly increase significantly on the TP. There is a decrease in the amount and days of intense precipitation in Southwest China, and south of Central Asia, with most decreasing trends insignificant at the 0.05 confidence level. The increasing/decreasing trends in intense precipitation intensity are like those of the amount and days, but the absolute values of the change rates are smaller and less significant (Fig. 3). In summary, there was a significant increased tendency of intense precipitation in most areas of the TP and a heterogeneous change in other areas of the HKH region. However, the reduction in every category of precipitation in southwestern China appears to be consistent with the reported weakening of the Indian summer monsoon over the past century (Ding and Ren, 2008).

The RX1DAY, RX3DAY, and RX5DAY all show significant gains over the study period (Fig. 4). There are insignificant discrepancies between the change characteristics of PA and

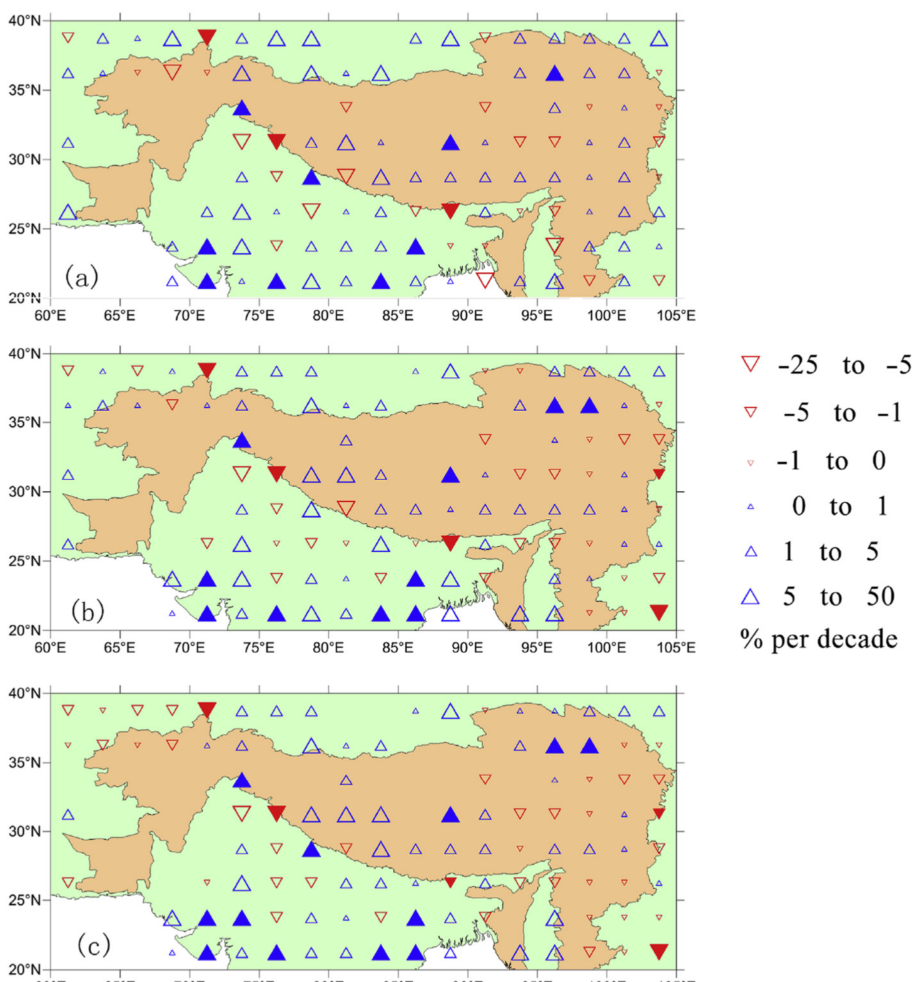

Fig. 5. Changing trends (% per decade) in percentage anomaly of (a) RX1DAY, (b) RX3DAY, and (c) RX5DAY over 1961–2012 in the HKH. Filled-in symbols represent statistically significant trends at the 0.05 confidence level.

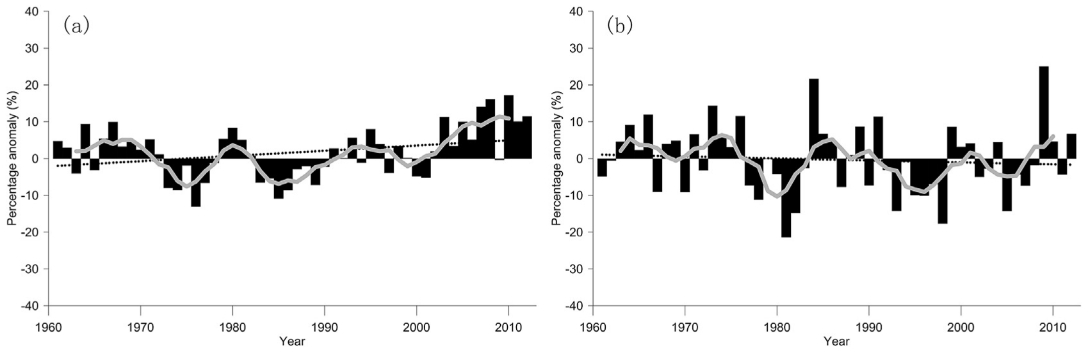

Fig. 6. Regional average percentage anomaly of (a) consecutive wet-days and (b) consecutive dry-days over 1961–2012 in the HKH. Gray line represents 5-year moving average, and dotted line shows linear trend.

NA; although the PA and NA of RX1DAY, RX3DAY, and RX5DAY all fluctuate prior to 1990, they rapidly shift to showing strong positive anomalies after 1990. Linear trends for regional average RX1DAY, RX3DAY, and RX5DAY are 2.14% per decade, 2.26% per decade, and 2.34% per decade, respectively, all of which are significantly at the 0.01 confidence level (Table 1).

There was an increase in RX1DAY (Fig. 5a) in most areas of the HKH, but this is not significant at the 0.05 confidence level. RX1DAY, RX3DAY, and RX5DAY all show increasing trends in India south of 25°N, which pass the 0.05 significance level in the coastal areas RX3DAY and RX5DAY insignificantly increase on the TP, but show decreasing trends in Southwest China. The change rates of RX1DAY (Fig. 5a) and RX3DAY (Fig. 5b) are small in the north of the southern Central Asia, but trends of RX5DAY (Fig. 5c) are negative in this region.

There were four peaks and three troughs for the variations of consecutive wet-days over the study period: peaks in the 1960s, in approximately 1980, approximately 1995, and in the 2000s; troughs in the 1970s, 1980s, and in approximately 2000 (Fig. 6a). Anomalies of consecutive wet-days were nearly all positive after 2001, with the exception of 2009. Consequently, the linear trend of PA of consecutive wet-days is 1.41% per decade, passing through the 0.05 significance test. However, changes in consecutive dry-days fluctuate, but the change characteristics are not apparent during the study period; the linear trend of the PA of consecutive dry-days is −0.534% per decade, which is not significant at the 0.05 confidence level. It is therefore evident that continuous rainfall tends to be heavier (Figs. 4 and 5) and lasts longer (Figs. 6a and 7a) in most parts of the HKH.

Consecutive wet-days significantly increased in India, except for in the Ganges drainage basin, and insignificantly increased on most parts of the TP (Fig. 7a). However, there was a significant decrease in consecutive wet-days in southwest China and west Asia (Fig. 7b). The spatial distribution pattern of consecutive dry-days trends is nearly opposite to that of consecutive wet-days; consecutive dry-days decreased

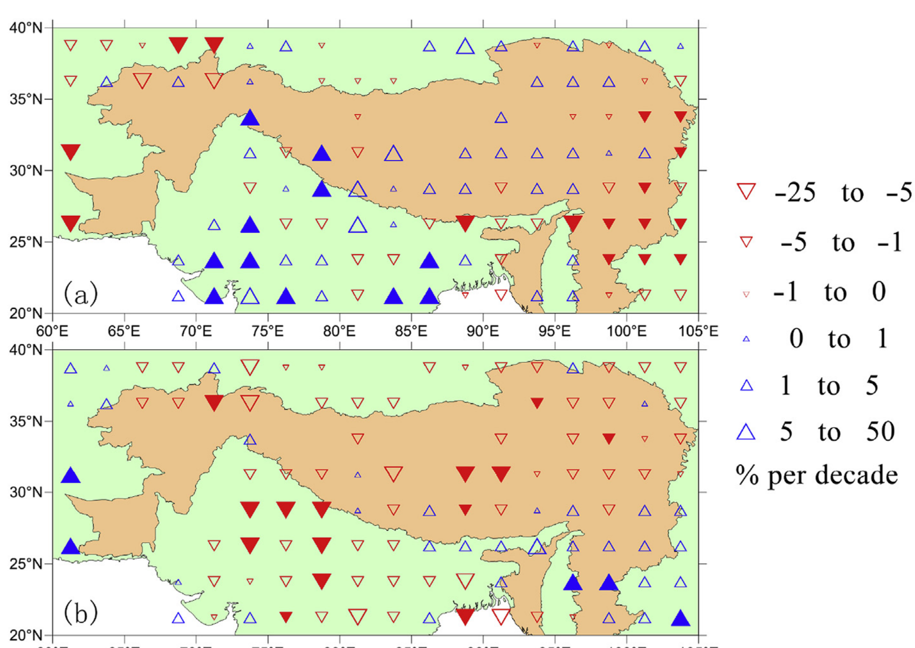

Fig. 7. Trends (% per decade) in percentage anomaly of (a) consecutive wet-days and (b) consecutive dry-days during 1961–2012 in the HKH. Filled-in symbols represent statistically significant trends at the 0.05 confidence level.

in most parts of India and the TP, and significantly decreased in Western India and in several grids in the eastern TP. However, consecutive dry-days increased in southwestern China and West Asia. The decreasing consecutive dry-days on the TP and in India is similar to that found by Alexander et al. (2006).

4. Conclusions and discussion

This paper uses a new multi-source dataset (CMA GLDP-V1.0) to analyze changes in extreme precipitation events over the HKH during 1961–2012. The main conclusions can be summarized as follows:

(1) There was a significant increase in light precipitation amount and days over various parts of India and the northern TP, but a significant decrease in light precipitation intensity in most areas west of 85°E. The regional average amount and frequency of light precipitation events in the entire HKH increased significantly during 1961–2012.
(2) The amount and frequency of moderate precipitation mostly increased on the TP, in the Tarim Basin, and in the Indian area south of 25°N, but regional average trends were not significant with the exception of the PA of wet-days.
(3) The amount and frequency of intense precipitation mostly increased significantly on the TP, and in the Taklimakan Desert and India, but decreased insignificantly in the Southwest China and in southern Central Asia. However, the spatial patterns of trends in intense precipitation intensity are similar to that of the intense precipitation amount and frequency, with less significant trends in most parts of the HKH. There was a significant increasing trend in regional average intense precipitation amount and frequency over the HKH during 1961–2012.
(4) The regional average RX1DAY, RX3DAY, and RX5DAY all significantly increased during 1961–2012, and the increase was relatively spatially consistent throughout the study region. These findings indicate that short-term continuous heavy rain increased during the study period.
(5) The number of consecutive wet-days tended to increase significantly in most parts of the HKH, and the regional average number of consecutive wet-days also significantly increased during 1961–2012. The changing pattern for consecutive dry-days was opposite to that of consecutive wet-days, but the regional average consecutive dry-days showed no noticeable trend during 1961–2012.

Although the conclusions made in this paper are similar to those of previous studies, some of the results reported here differ. For example, certain results are different from those of previous studies for mainland China (Zhai et al., 2005), and also with respect to the significant increase in the amount and number of days of light precipitation over various parts of India and the northern TP, and of the regional average amount and frequency of light precipitation for the whole HKH. However, the differences may be related to the definition of a wet-day, which is defined as no less than 1 mm in this paper while previous studies for mainland China have mostly defined wet-day as a day with precipitation no less than 0.1 mm. Therefore, it could be interpreted that the decreasing number of wet-days in mainland China mainly refers to a decrease in drizzle, which always provides less than 1 mm of daily precipitation but more than 0.1 mm per day (Liu et al., 2005).

Daily data obtained from the CMA GLDP-V1.0 dataset are of better quality and are more valid than those from any other single dataset (such as GHCN-D) used in previous works (Menne et al., 2012); however, they are still spatially and temporally insufficient for many parts of the HKH (including Afghanistan, Pakistan, Myanmar, Bhutan, and the northwestern part of the TP). The temporal and spatial sparseness is the major source of uncertainty in estimating long-term trends of extreme precipitation in the HKH, because analysis of percentile-based extreme indices requires sufficient wet-day records. The method used for selecting stations retains a large amount of missing data, and this can also cause uncertainties. For example, if the amount of missing data is temporally inhomogenous during the study period, estimations of change rates in precipitation indices will be inaccurate. Although grid values, which are the average of all station values in a grid, can be calculated using non-missing values from other stations, they remain sensitive to missing data. In addition, if the values of grids with many stations are obtained from different stations in differing years, then temporal inhomogeneity will appear. It is thus currently difficult to correct the inherent inhomogeneity.

The spatial sparseness of station data also plays a vital role in causing uncertainties. Extreme precipitation can vary strongly over short horizontal distances due to orographic effects; however, high-altitude precipitation gauge networks are almost non-existent. Even when gauges exist in these areas, they are mostly located in valleys where precipitation amounts are smaller compared to those at higher altitudes, and thus cannot represent the complex topography and spatial change in precipitation (Reggiani and Rientjes, 2015). In addition, most gauges have difficulties in accurately capturing precipitation, particularly for winter snowfall. Direct snow-accumulation measurements using snow pillows, pits, and cores from accumulation zones are also scarce and usually only cover short periods. Furthermore, a decreasing wind speed (Jiang et al., 2009; Vautard et al., 2010; You et al., 2010; Guo et al., 2011) can affect rain gauge measurements (Yang et al., 2005), and this may be one of the reasons for the increasing amount of light precipitation found in this study. Moreover, as the distribution of extreme precipitation has a very local feature, especially in high attitude areas, many data that appear to be disputable cannot be examined in the dataset because of the sparseness of the observational data. Improvement in data coverage is currently under way, and certain historical data rescue plans, including that of the earth circulation reconstruction initiative (Williamson et al., 2016) can also provide a solution to this issue, but a certain amount of time is required to obtain records that are long enough to enable a more accurate analysis.

Uncertainties with observational studies are also related to gaps in studies, including data processing and analytical methods. The regional average PA and NA show similar change patterns for RX1DAY, RX3DAY, RX5DAY, consecutive wet-days, and consecutive dry-days, but there are large differences in the change patterns of the percentile-based categories of precipitation between PA and NA. One reason for this is that the grid value of PA would be enormous if only a few stations in this grid were located in the extreme arid region and if one of these stations had an abnormally high precipitation record, as this would ultimately cause a false high regional average value. To solve this problem, further analyses are required that focus on the applicability of precipitation indices. The regional average method is not very robust when the data quality is poor. For example, grids size and the initial latitude and longitude can also affect the averaged time series. Therefore, further research is currently being conducted, which is aimed at evaluating a regional average method under varied data quality.

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