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Characterising spatiotemporal variability of South Asia's climate extremes in past decades

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ABSTRACT: We systematically examined past spatiotemporal changes in climate variability to gain some cross-regional insights into South Asia's vulnerability to extreme conditions. Gridded Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) precipitation and Princeton Global Meteorological Forcing Dataset (PRINCETON) temperature data from 1975–2004 were used to derive a suite of annual extreme indices. Long-term mean and decadal variations of these indices were mapped. Long-term change tendencies were also detected from a suite of 'slope' maps composed by the 30 yr change trend at each grid cell in the region. Most precipitation indices indicated a tendency towards drier conditions, whereas all temperature indices marked a steady coherent warming trend. The extremely wet day precipitation index exhibited the largest change, indicating an increase in heavy precipitation in South Asia. The highest maximum temperature extreme showed increases, indicating more unbearable heatwaves in the region. These trends present a previously unrecognised regional picture of the patterns and trends in historical climate extremes, with each grid cell representing spatiotemporal characteristics of changes. The present study is superior to most studies that only summarise an averaged regional trend from tendencies over large areas, and therefore will improve trans-boundary understanding of extreme climates in South Asia. Our study also exemplifies the application of existing gridded regional/global data sets. It provides valuable means of cross-regional information for bridging gaps where gauging observations are unavailable, particularly in data-poor developing countries.

KEY WORDS: Climate variables · Indices of extreme conditions · Gridded daily climate data · Change trend

1. INTRODUCTION

It is well recognised that changes in the frequency and intensity of extreme climate events have profound impacts on both human society and the natural environment (Easterling et al. 2000). One of the most vulnerable regions to climate extremes is South Asia, in view of the huge population, extensive food insecurity and unsustainable soil and management practices on marginal lands in the semi-arid areas. According to the World Bank (Bronkhorst 2012), the number of disasters reported per year in the South Asia Region has increased 5-fold over the past 4 decades, affecting over 2 billion people and causing 825 000 deaths. Resulting direct economic losses have accumulated to over USD $80 billion without

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accounting for substantial indirect losses. Flood events caused by extreme precipitation are the most common natural hazard in South Asia, where 64% of the world's total population is exposed to floods each year. According to Bronkhorst (2012), floods have accounted for approximately half of all disaster events over the past 40 yr, have impacted approximately 82% of all individuals affected by disasters and were responsible for 80% of all economic loss caused by disasters in the region. In the past 10 yr alone, it is estimated that the countries in this region have suffered over USD $50 billion worth of damages.

The Intergovernmental Panel on Climate Change (IPCC) provided specific information for the South Asia region concerning the nature of future inevitable impacts (Barros et al. 2014). These impacts will result from increased climate variability including more variable precipitation, and more frequent floods and droughts, and will continue to intensify in the coming decades. Climate change poses challenges to sustainable development in South Asia. Taking water resource management as an example, many countries in the region share common geological formations and river basins, and natural events frequently cross national boundaries. Though adapting to climate change requires local and national actions, these need to be informed by regional-level changes in extreme climate and consequent impacts on flooding and drought across all these river basins.

Over the last decade, there have been many published studies addressing the frequency of climate extremes at large spatial extents, i.e. national (Easterling et al. 2000, Agarwal et al. 2014), regional (Aguilar et al. 2005, Zhang et al. 2005, Min et al. 2011, Donat et al. 2014, Rajbhandari et al. 2018) and global (Alexander et al. 2006, 2009, Donat et al. 2013, Mishra et al. 2015). Many climate researchers use point-based time series analysis of climate variables to underpin their analyses. This requires long-term climate station observation data. Unfortunately, such data sets are limited, particularly in South Asia, and as a consequence, there are few similar studies with a primary regional focus on South Asia. Little information on trends and variability in climate extremes is available for the region, especially their spatiotemporal distributions (Manton et al. 2001, Klein Tank et al. 2006). In addition, most of the previous studies were conducted at a national and/or basin scale (Sen Roy & Balling 2004, Zahid & Rasul 2011, Shrestha et al. 2017). The analyses conducted by different researchers in different countries may not seamlessly merge together to form a larger regional view because the analyses might have been conducted on different indices, or using different methods, or at different spatiotemporal scales. On the other hand, even national scale climate is a (spatial) part of a larger regional climate process which is primarily driven and governed by synoptic scale climatic driving forces. Understanding such 'local' climate variation within a larger regional scope will help us better understand extreme climates, their driving forces and impacts in the region. As such, there is a need to develop, calculate and analyse a suite of regional indices of climate extremes in South Asia. A study on the distribution, frequency and intensity of extreme climates across the whole region using higher spatiotemporal daily data sets is necessary. The outcomes can provide useful insights for resource planners, system managers and policy makers concerning climate variability and change for their responsible operations and resource management.

Station data are the primary source for climate change and variability studies. However, these observations are often biased and distributed inhomogeneously in space and time. There can be missing data, unknown errors attributed to certain observation methodologies and, more importantly, a change of methodology can lead to a systematic bias (Pai et al. 2014). Most importantly, changes in climate at the regional scale are largely the result of variability in larger scale atmospheric circulation patterns. It is, therefore, necessary to convert station data to a regular space–time grid and to correct or remove the erroneous values before such observations can be used for large-scale diagnostic studies (Pai et al. 2014), which may also involve meteorological reanalysis. This has led to the generation of several global, continental and regional gridded climate data sets on a daily scale. These include the Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) of the water resources (Yatagai et al. 2012), the Princeton Global Meteorological Forcing Dataset (PRINCETON; Sheffield et al. 2006), the Water and Global Change (WATCH) data set (Harding & Warnaars 2011) and the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) data set (Funk et al. 2015). These data sets, however, differ in (1) spatial and temporal resolutions, (2) spatial and temporal coverages, (3) types of basic observations (e.g. rain-gauge or satellite-based precipitation), (4) methods used for interpolation of data from the sample points (rainfall gauges) to the grid cells and (5) models used to assimilate climate variables and conditions/states (Pai et al. 2014). Nevertheless, these quality-controlled gridded data sets provide valuable means of regional analysis to fill the gaps where gauging observations are unavailable, thereby allowing us to place recent climate extremes into historical context while looking ahead to the future.

A number of studies have been conducted on the validation of the APHRODITE and PRINCETON data. In general, evaluation results indicate that both are suitable for climate analysis in South Asia due to not only their higher spatiotemporal resolutions, but also their larger coverage and the longer time series in comparison with other gridded climate data sets. APHRODITE has substantially improved the depiction of the areal distribution and variability of precipitation around the Himalayas and Southeast Asia (Yatagai et al. 2012). A comparison between APHRODITE and the TRMM (Tropical Rainfall Measuring Mission) precipitation estimations revealed that the use of best possible available observation data in APHRODITE has resulted in the generation of one of the most reliable daily precipitation products over Nepal and the Himalayan region (Duncan & Biggs 2012). Ghulami et al. (2017) verified gridded daily precipitation estimates from 4 satellite/global products over the Kabul basin in Afghanistan. They found that APHRODITE was the best, i.e. with lowest errors, despite the fact that it generally underestimates during winter and overestimates during the dry period. Andermann et al. (2011) qualitatively assessed the reliability of the APHRODITE daily precipitation data along the Himalayan range. Lutz & Immerzeel (2013) validated APHRODITE data against actual station data for observed precipitation in upstream river basins that are primarily characterised by snow and glacial melt. Both of these studies found that APHRODITE can provide more accurate overall precipitation estimates than other regional/global gridded data sets, although it underestimates high-altitude precipitation. PRINCETON temperature was compared with the observed data from India Meteorological Division (IMD). The two data sets were found to be consistent with spatiotemporal variability and for correlations between precipitation and air temperature (Shah & Mishra 2016).

In this study, we mapped regional climatic variability using a suit of extreme indices derived from gridded land-based APHRODITE and PRINCETON data sets in South Asia. Our goal was to investigate cross-region extreme precipitation and temperature to identify how historical climate extremes are likely formed in spatial and temporal domains and to quantify key changes which mark the trends of climate variations in the last decades. This work also contributes to the elevation of research potential for data-poor, developing countries that have conducted a paucity of climate extremes analyses because of insufficient resources to undertake such analyses, including lack of reliable data sets, few digitized records and poor data quality.

2. DATA AND METHODS

2.1. Data source

We obtained gridded daily climate data from APHRODITE and PRINCETON. The key features of the APHRODITE and PRINCETON data sets are summarised in Table 1.

APHRODITE is a database of 0.25° (~25 km) gridded daily precipitation and temperature for continental Asia. It was developed by the Research Institute for Humanity and Nature and the Meteorological Research Institute of the Japan Meteorological Agency. The gridded data set is obtained by interpolating on-ground precipitation measurements. In South Asia, the network of precipitation stations used in APHRODITE precipitation is dense in India and the northeast of the region, but very sparse in Pakistan and the Himalayan region. APHRODITE precipitation has been used for numerous regional Asian hydroclimate studies, including determination of Asian monsoon precipitation change, evaluation of water resources, verification of high-resolution model simulations and satellite precipitation estimates, and improvement of precipitation forecasts (Yatagai et al. 2012). Recently, Xie et al. (2013) investigated droughts in Pakistan, and Duncan et al. (2013) explored temporal trends in the Indian summer monsoon. Agarwal et al. (2014) analysed future precipitation in the Koshi River Basin in Nepal. Aadhar & Mishra (2017) developed a high-resolution near real-time drought monitoring system in South Asia. Rajbhandari et al. (2018) used both APHRODITE precipitation and temperature in the projection of future climate change over the transboundary Koshi River Basin.

The PRINCETON data product is a global 0.5° (~50 km) gridded data set of daily climate data from 1948–2008. It was developed and is managed by the Terrestrial Hydrology Research Group at Princeton University. The data are derived by combining reanalysis data with meteorological forcings, satellite data and ground-based observations. This data set provides a long-term, globally consistent data set of near-surface meteorological variables, including precipitation, temperature, solar radiation, specific humidity, surface pressure, wind speed and elevation. PRINCETON temperature has been widely used in

Table 1. Summary of Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) and Princeton Global Meteorological Forcing Dataset (PRINCETON) data sets

Dataset	APHRODITE	PRINCETON
Name	Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources	Princeton Global Meteorological Forcing Dataset
Spatial coverage	Continental Asia	Global
Period of data	1951–2007 (Precipitation) 1961–2007 (Temperature)	1948–2008
Temporal resolution	Daily	Daily
Spatial resolution	0.25 × 0.25 degree (~25 km)	0.5 × 0.5 degree (~50 km)
Type	Interpolation from on-ground precipitation stations	Reanalysis data combining meteorological forcings, satellite data and on-ground observations
Variables	Precipitation (mm d^{-1}) Temperature (°C)	Precipitation (kg m^{-2} s^{-1}) Air temperature at 2 m above ground (K) Maximum air temperature (K) Minimum air temperature (K) Downward longwave at surface (W m^{-2}) Downward shortwave at surface (W m^{-2}) Surface pressure (Pa) Specific humidity (kg kg^{-1}) Wind speed (m s^{-1}) Elevation (m)
Format	NetCDF	NetCDF
Provider	University of Tsukuba, Japan	Princeton University, USA
Key strengths	Highest resolution gridded daily precipitation and temperature data sets covering continental Asia Widely used for numerous hydroclimate studies in countries/basins	Gridded data set for the range of climate variables with global coverage Widely used for numerous regional and global modelling studies in various disciplines Temperature data include daily mean, minimum and maximum records
Key limitations	Station network changes with time and season Poor station coverage in some regions (for South Asia, poor coverage in Pakistan and Himalaya region) Temperature data only have daily mean records	Blending reanalysis data with observations and disaggregates in time and space (compared to APHRODITE and India Meteorological Division (IMD) which interpolate precipitation observed at a much larger number of stations). Daily precipitation data are likely to be poorer than APHRODITE and IMD. Monthly data and trends are more acceptable. Other climate data are reasonable because unlike precipitation, they are much more conservative in space and time.
Download portal/ source	www.chikyu.ac.jp/precip/english/ products.html	http://hydrology.princeton.edu/data.php

numerous regional and global hydroclimate, land surface, hydrological and ecohydrological modelling studies (Sheffield et al. 2006, 2009, 2012, Sheffield & Wood 2007, Wang et al. 2011). Recently, PRINCETON temperature was used to evaluate changes in hydro-climatic variables over the Indian subcontinental basins (Shah & Mishra 2016) and for drought monitoring in South Asia (Aadhar & Mishra 2017).

For this study, a popular 30 yr period from 1975–2004 was chosen based on data availability and the IPCC benchmarked period (Barros et al. 2014). Daily data were extracted from the APHRODITE precipitation (hereafter Aphrodite-Precipitation) and PRINCETON temperature (hereafter Princeton-Temperature).

2.2. Quality assurance

Given the above-mentioned existing validations, a simple further data quality assurance procedure was undertaken in this study at 2 levels — regional/national and basin/catchment — using the best available data at higher resolution. Annual, seasonal and monthly Aphrodite-Precipitation and Princeton-Temperature data were checked against the high-resolution IMD data and PMD (Pakistan Meteorological Department). The IMD precipitation data set provides a 0.25° (~25 km) gridded daily record across India from 1901–2013. The IMD temperature data set provides a 1° (~100 km) gridded daily temperature record across India from 1969–2009. Both were derived by interpolating observations from meteorological stations across India. Detailed descriptions of the data sets and comparative analysis can be found in Rajeevan et al. (2005) and Pai et al. (2014) for precipitation, and in Srivastava et al. (2009) for temperature. PMD daily precipitation data at 1 km resolution were collected from modelled grids of 41 synoptic meteorological stations across Pakistan (Zahid & Rasul 2011).

The precipitation comparisons were conducted in the overlapping area and common period among the APHRODITE and IMD data sets. Results in mean annual and seasonal precipitation (Fig. 1) shows that IMD precipitation is well represented in the Aphrodite-Precipitation. Errors or uncertainties in the APHRODITE data are illustrated in Fig. 2. It maps the ratio of Aphrodite-Precipitation to locally collected 1 km resolution gridded PMD precipitation for the upper catchment area of the Indus Basin primarily characterised/dominated by snow and glacial melt. There is a good agreement in low-altitude precipitation (black areas in Fig. 2), but an underestimate in high-altitude precipitation (green areas in

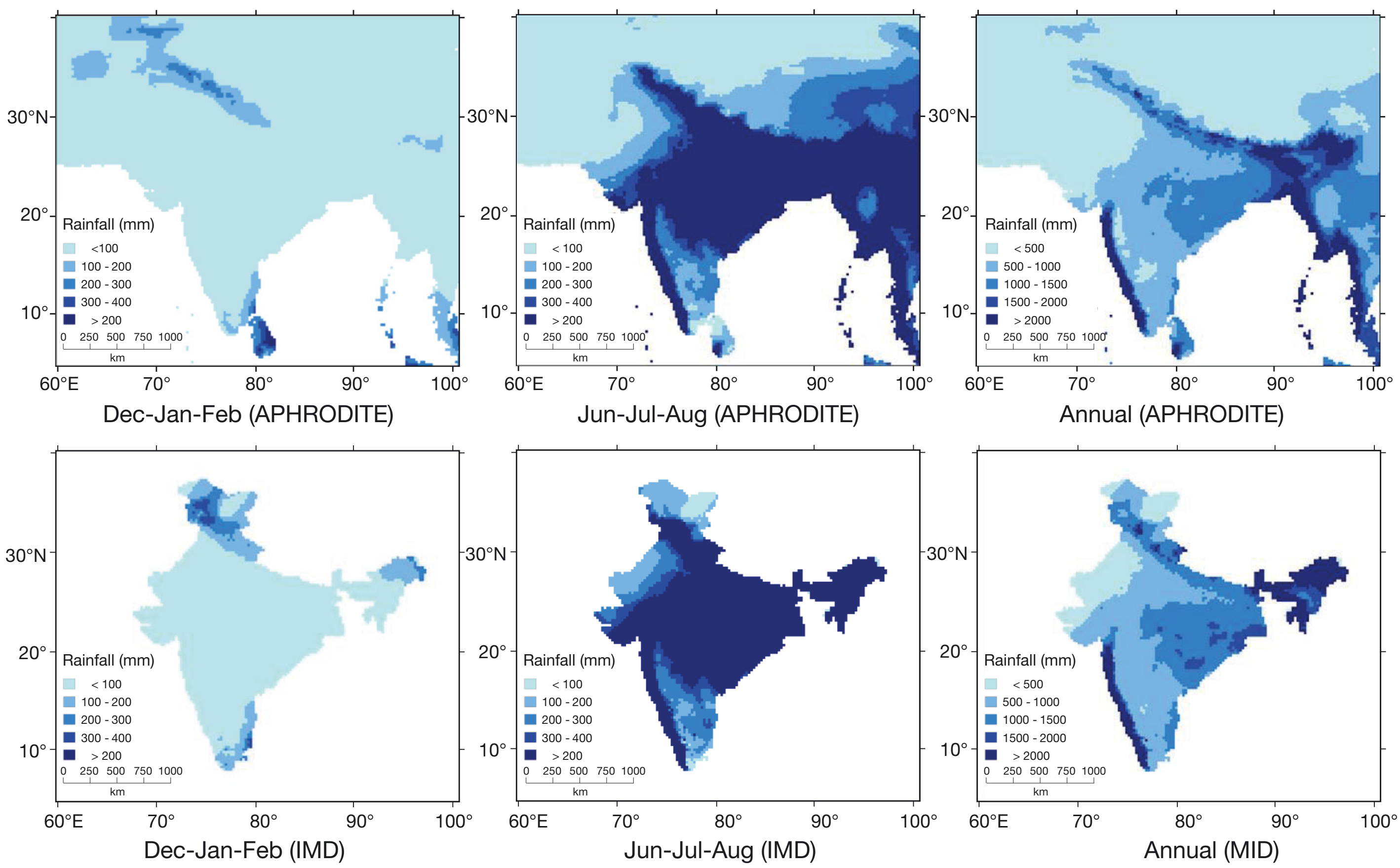


Fig. 1. Example of mean annual and seasonal precipitation comparisons at regional/national level (Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation [APHRODITE] vs. India Meteorological Division [IMD])

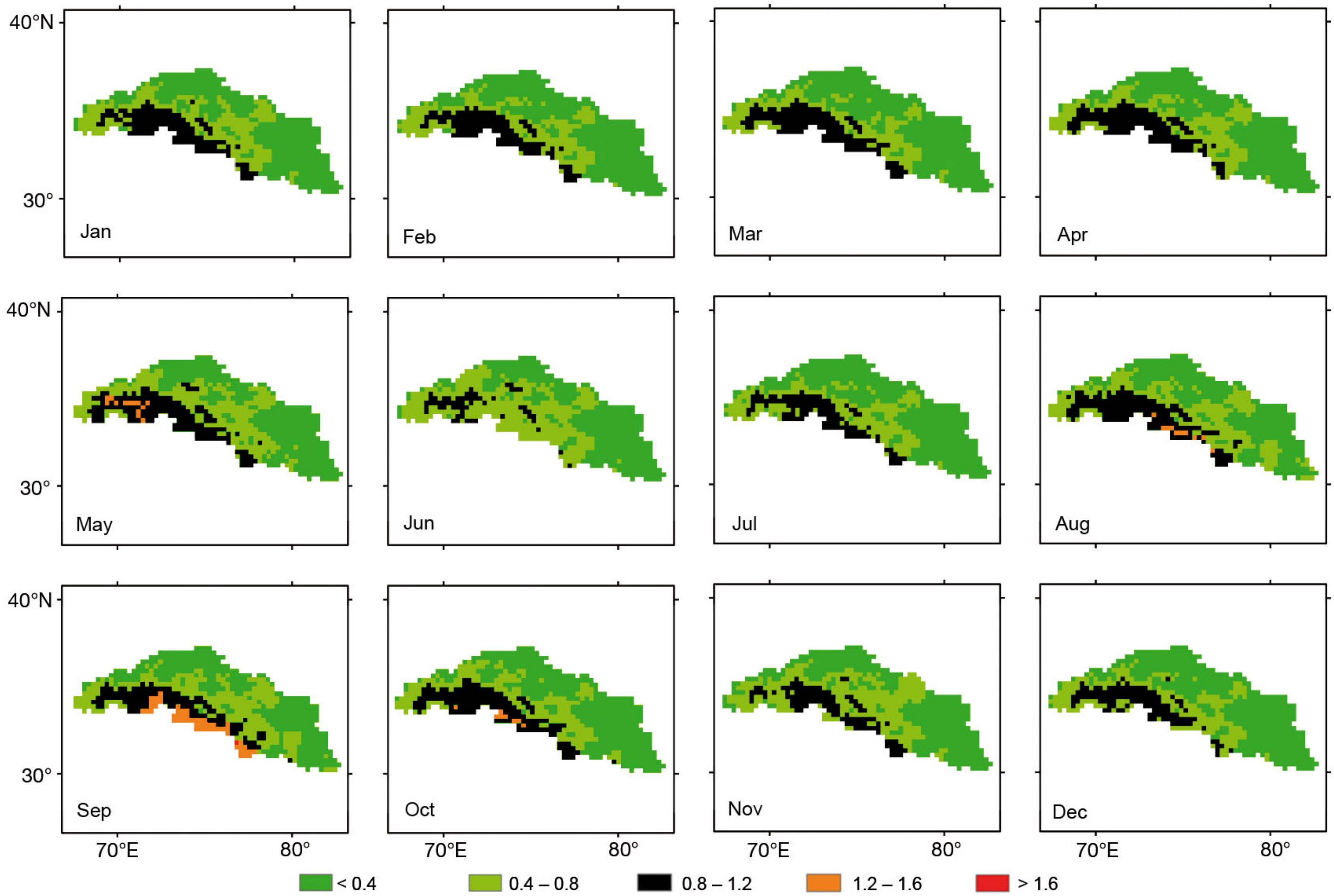


Fig. 2. Ratio of Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) to Pakistan Meteorological Department (PMD): example of mean monthly precipitation comparisons at basin/catchment level (upper Indus Basin)

Fig. 2). Underestimation in high-elevation precipitation in mountainous areas was also recognised by previous studies, such as Immerzeel et al. (2015) and Dahri et al. (2016, 2018). This may prevent an accurate estimate of altitudinal precipitation extremes.

Precipitation data from APHRODITE and IMD are consistent for month-to-month variability and bias (Figs. 1 & 2) as documented by Prakash et al. (2015) and Hussain et al. (2017). Temperature data from PRINCETON and IMD agree reasonably well (Fig. 3), as reported in Shah & Mishra (2016). In general, evaluation results indicate that both Aphrodite-Precipitation and Princeton-Temperature are suitable for climate analysis in the South Asia region. Major errors or uncertainties in both data sets occur in high-altitude mountain ranges, noticeable as underestimates in Aphrodite-Precipitation and overestimates in Princeton-Temperature.

2.3. Extraction of extreme indices

Climate extremes can be placed into 2 broad groups. One consists of simple statistics-based extremes, such as very low or very high daily temperatures, or heavy daily or monthly rainfall amounts, which occur every year; the other consists of more complex event-driven extremes, examples of which include drought, floods or hurricanes, which do not necessarily happen every year at a given location (Easterling et al. 2000). Since South Asia spans a broad range of climates, a suite of 30 standardised indices that characterise climate variables and extreme conditions, including amount, frequency and intensity of precipitation and temperature, were employed in this study (Table 2). They were adapted from those published by the Australian Bureau of Meteorology (www.bom.gov.au/climate/change/about/

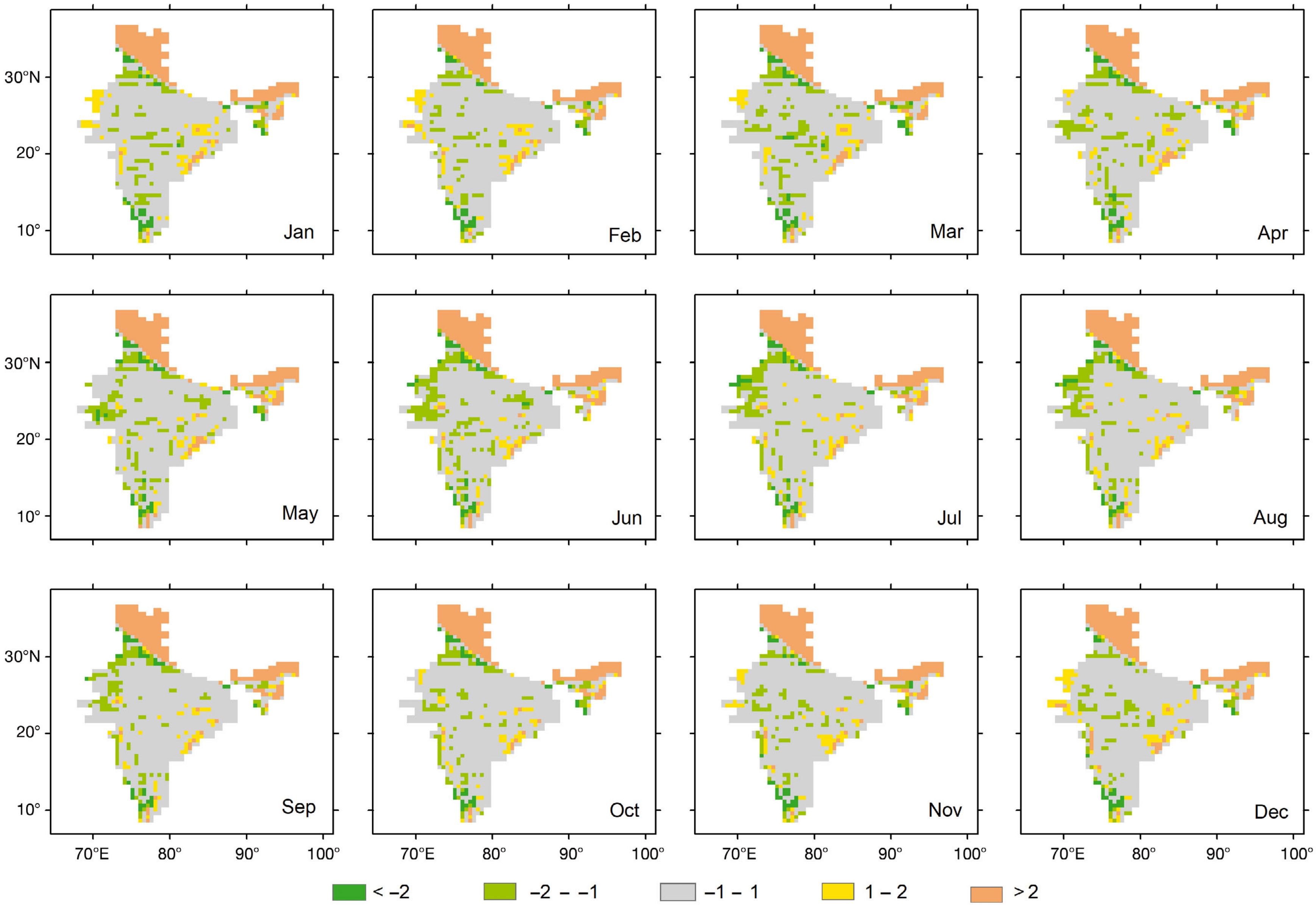


Fig. 3. Difference between Princeton Global Meteorological Forcing Dataset (PRINCETON) and India Meteorological Division (IMD): example of long-term mean monthly temperature (°C) comparisons at the national level (India)

Table 2. Extreme indices adopted in this study. All 30 indices are available as data sets. **Bold**: top 15 indices mapped in this paper

Extreme indices	Definition
Annual total wet day precipitation	Annual total precipitation on wet days (daily precipitation ≥1 mm)
Extreme wet day precipitation	Annual total precipitation when daily precipitation >99th percentile
Simple daily intensity	Annual total precipitation divided by the number of wet days (daily precipitation ≥1 mm)
Consecutive dry days	Maximum number of consecutive days with daily precipitation <1 mm
Consecutive wet days	Maximum number of consecutive days with daily precipitation ≥1 mm
Wet days	Annual count of days with daily precipitation ≥1 mm
Very heavy precipitation days	Annual count of days with daily precipitation ≥30 mm
Maximum 1 d precipitation	Annual maximum 1 d precipitation total
Frost nights	Annual count of nights with minimum temperature <0°C
Cold spell duration	Annual count of nights with ≥6 consecutive nights when daily minimum temperature <10th percentile
Hot days	Annual count of days with maximum temperature >35°C
Hot nights	Annual count of nights with minimum temperature >20°C
Warm spell duration	Annual count of days with ≥4 (or 6) consecutive days when daily maximum temperature >90th percentile
Highest maximum temperature	Annual maximum value of daily maximum temperature
Growing season length	Annual (1 Jan to 31 Dec) count between first span of ≥6 d with daily mean temperature >15°C and first span of ≥6 d with daily mean temperature <15°C
Heavy precipitation days	Annual count of days with daily precipitation ≥10 mm
Maximum 5 d precipitation	Annual maximum consecutive 5 d precipitation total
Very wet day precipitation	Annual total precipitation when daily precipitation > 95th percentile
Very hot days	Annual count of days with maximum temperature >40°C
Very hot nights	Annual count of nights with minimum temperature >25°C
Cold days	Annual count of days with maximum temperature <15°C
Very cold days	Annual count of days with maximum temperature <10°C
Cold nights	Annual count of nights with minimum temperature <5°C
Warm days	Percentage of days with maximum temperature >90th percentile
Warm nights	Percentage of nights with minimum temperature >90th percentile
Cool days	Percentage of days with maximum temperature <10th percentile
Cool nights	Percentage of nights with minimum temperature <10th percentile
Highest minimum temperature	Annual maximum value of daily minimum temperature
Lowest maximum temperature	Annual minimum value of daily maximum temperature
Lowest minimum temperature	Annual minimum value of daily minimum temperature

extremes.shtml) based on the definitions from WMO Expert Team on Climate Change Detection Monitoring and Indices. In total, 15 indices (bolded in Table 2) are mapped and discussed in this paper; the others are only available as data sets.

In this study, 30 yr (1975–2004) daily gridded Aphrodite-Precipitation and Princeton-Temperature (maximum, minimum and mean) data were used to establish annual precipitation extreme indices (25 km resolution) and annual temperature extreme indices (50 km resolution), respectively. For each index, the gridded annual values of 30 yr were then aggregated to derive 3 decadal (1975–1984, 1985–1994 and 1995–2004) mean grids and a long-term mean grid.

2.4. Analysis of spatiotemporal change trends

We first derived inter-decadal changes for 3 decades 1975–1984 (D1), 1985–1994 (D2) and 1995–2004 (D3). Differential values between consecutive 10 yr mean values (D2–D1 and D3–D2) for each index were computed. Positive values show an increasing tendency, whereas negative values indicate a decreasing tendency. Long-term changes were measured by the trend slope of a linear regression line.

Conventionally, a linear 'trend' is represented by the slope of the linear trend line. In this study, the slope of the linear trend line for a given climate extreme index was computed from the time series data (30 annual index values) at each grid cell location. A 2-dimensional spatial map showing the slopes of all cells was constructed as a trend map of the region. A total of 30 trend maps representing 30 climate extreme indices can well illustrate the spatial distribution of their variation tendencies in the region, and reveal the regional patterns of long-term changes during the 30 yr time period of trend estimation.

3. RESULTS AND DISCUSSION

The precipitation and temperature analysis revealed a variety of multi-decadal and long-term changes in extreme values over 30 yr in South Asia. Although this is true for both climate elements, changes in temperature had a much higher degree of spatial coherence. This comes as no surprise since precipitation in the region has much higher spatio-temporal variabilities than temperature.

3.1. Changes in precipitation extremes

Spatial maps of selected key precipitation extreme indices are presented in Fig. 4; a 30 yr mean value map and 2 maps of differential values between consecutive 10 yr mean extremes (decadal mean change maps) are listed for each index. With higher differentials in the first 2 decadal change maps (D2–D1) than in the second 2 decadal change maps (D3–D2), there is a tendency towards reduced variation in precipitation extremes across almost all indices over the 30 yr. It should be noted that the increase in simple daily intensity and very heavy precipitation days in the southern half of Pakistan and Bangladesh makes flooding more frequent.

Other studies have asserted that there has been a decrease in extreme precipitation (e.g. Singh et al. 2014), which is well echoed by viewing the linear trend slope maps of some key precipitation indices used in this study (Fig. 5). The spatial distributions of long-term change trends for selected indices are shown in Fig. 5, where increases or decreases in trends at a specific location (within a 25 × 25 km pixel) are further demonstrated by time series plots. Fig. 5a is the linear trend slope of annual total wet day precipitation, which is practically identical to mean annual total precipitation. The map shows a decline in annual precipitation in most of the dry south parts of the region, while Fig. 5c illustrates an increase in consecutive dry days in most of India, south Pakistan, low-lying areas of southwest Afghanistan and the east corner of Iran. A particularly strong increase in consecutive dry days occurs in the triangle region of Afghanistan, Iran and Pakistan. Based on best data available, declining annual precipitation in conjunction with an increase in consecutive dry days could imply less water income and a higher drought probability, which would negatively affect the agricultural conditions and put more pressure on the management of already stretched water sources in this region.

Positive linear trend slope patterns, suggesting increasing annual precipitation, can be seen in Bangladesh, east Nepal, north Pakistan and the central highlands of Afghanistan. The trend slope map of consecutive dry days (Fig. 5e) shows corresponding patterns in those regions with a declining tendency, which signals growing wetter conditions. This is consistent with climate change patterns in the neighboring Tibetan Plateau and agrees with the findings of Baidya et al. (2008). Bangladesh shows a particularly strong positive linear trend of annual total wet day precipitation, which indicates a substantial increase of annual rainfall. There have been reports of increased tropical cyclones in the Bay of Bengal as the climate changes, which have brought more rainfall to the area (MoEF 2008).

The tendency for consecutive dry days is of increasing concern. Nepal shows an overall increase, with the exception of small areas in the mountains along its northern border. The finding that most of India and south Pakistan has become drier in the last decades attracts major attention. This confirms the results reported by Singh et al. (2014), which indicated an increase in the frequency of drought and increasing trend of consecutive dry days. This may be due to the rapid warming of the Indian Ocean (Roxy et al. 2015) and to atmospheric aerosols (Bollasina et al. 2011). Interestingly, among all countries in the region, the 30 yr linear trend of consecutive dry days in Afghanistan contrasts with the strongest declining trend in the northeast highlands, accompanied by the strongest increasing trend in the low-lying areas of the southwest region. Considering the limited scope to acquire quality-assured data in such a volatile political and harsh natural environment, the reliability of this index in Afghanistan is questionable (Aich et al. 2017, Ghulami et al. 2017). The maximum 1 d precipitation (practically rainfall) is a typical index used to characterise extreme rainfall events. While having a generally spotty/scattered distribution, the linear trend slope map of maximum 1 d precipitation suggests an increasing trend of extreme daily rainfall events along with the main path of southwest summer monsoon in India, Bangladesh and the west coast of Burma. The trend can be attributed to increased tropical cyclones in the Bay of Bengal. According to Francis & Gadgil (2006), most of the offshore convective systems, particularly those associated with troughs and/or vortices, are responsible for intense rainfall along the west coast of India. They also found that these convective systems are linked to the atmospheric conditions over the equatorial Indian Ocean. The finding along the northern parts

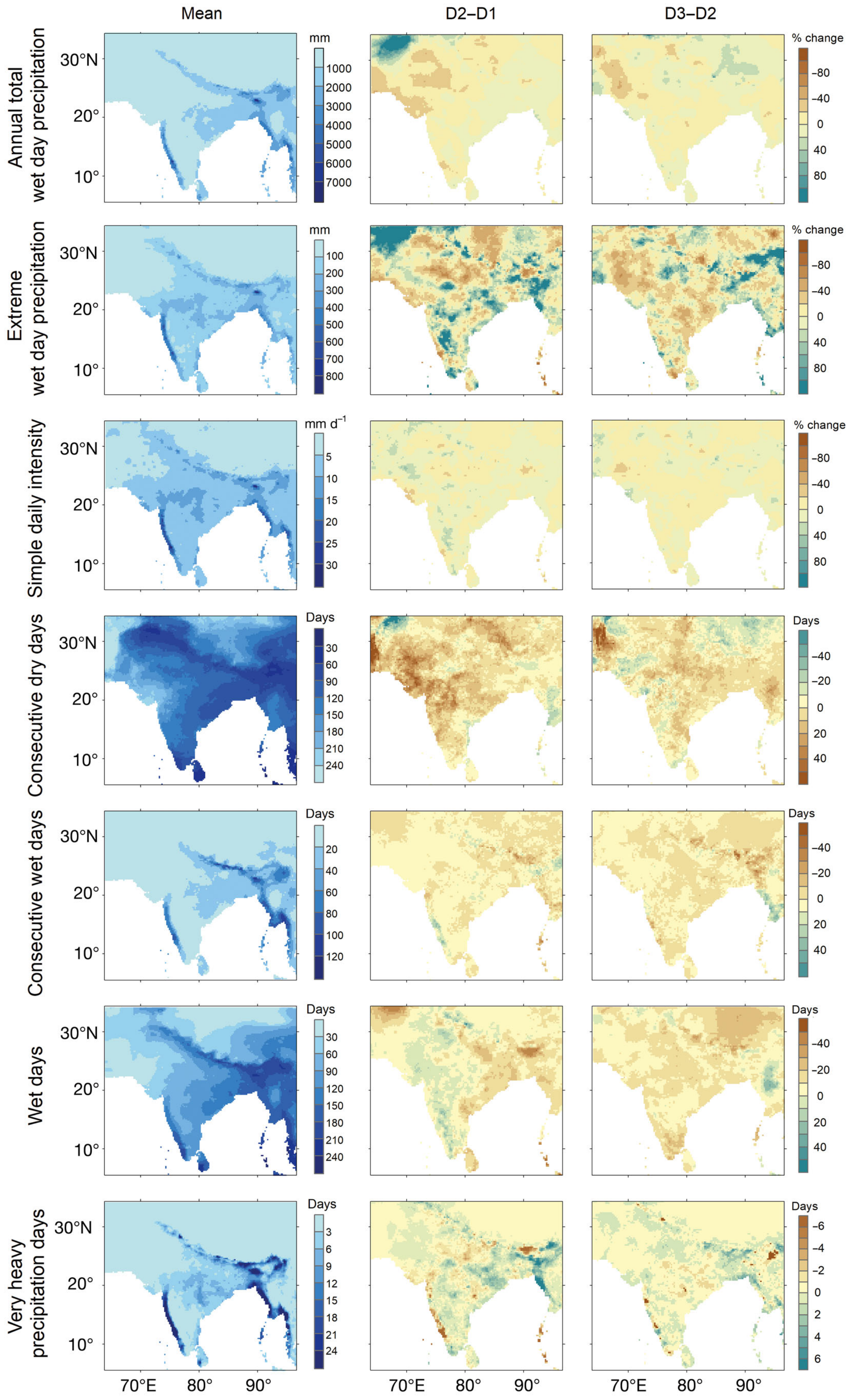


Fig. 4. Long-term mean and decadal changes of key precipitation extreme indices. Mean: 30 yr (1975–2004) mean distribution; D2–D1: differential values between the first 2 decades (1985–1994 and 1975–1984); and D3–D2: differential values between the last 2 decades (1995–2004 and 1985–1994)

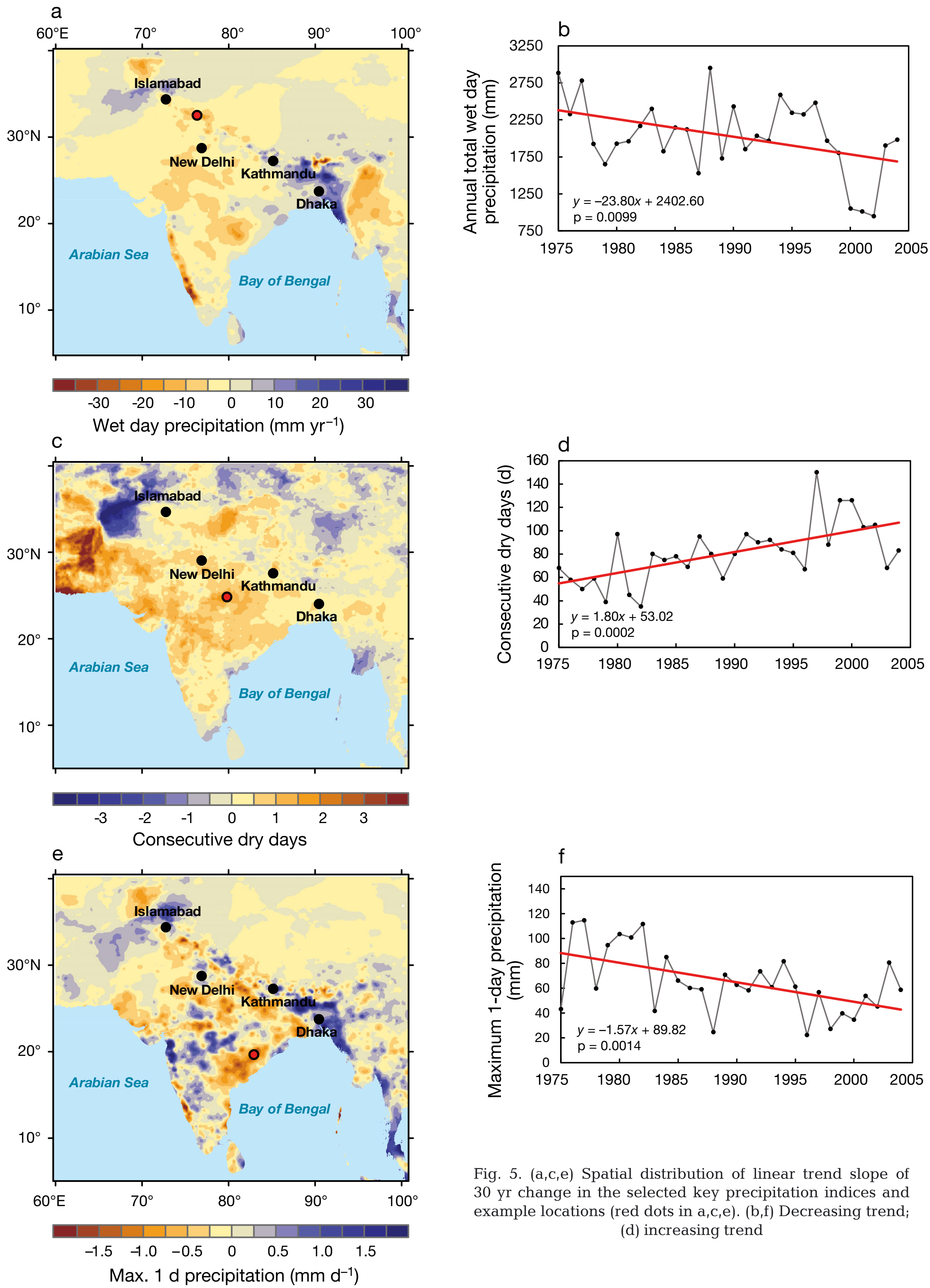


Fig. 5. (a,c,e) Spatial distribution of linear trend slope of 30 yr change in the selected key precipitation indices and example locations (red dots in a,c,e). (b,f) Decreasing trend; (d) increasing trend

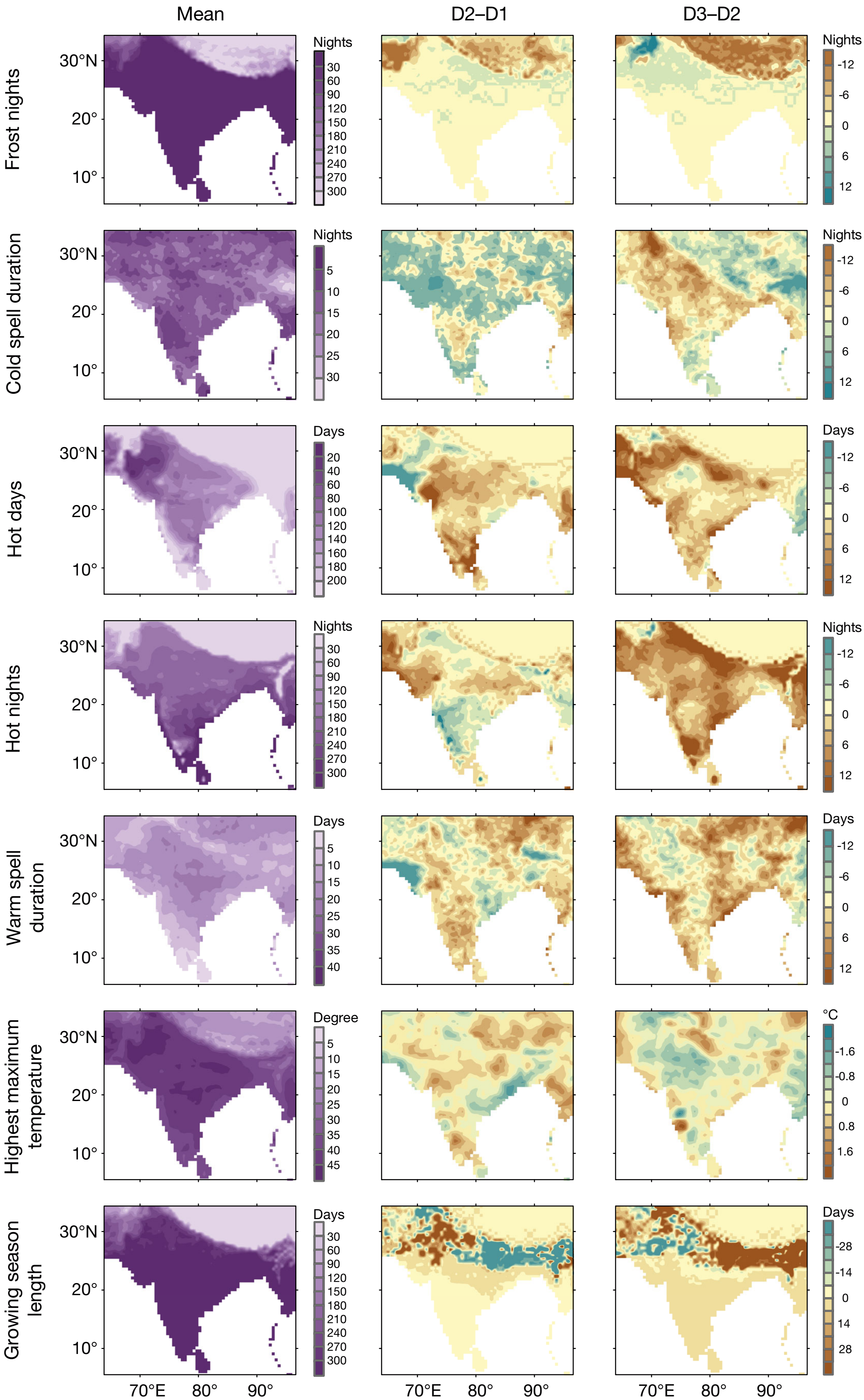


Fig. 6. Long-term mean and decadal changes of key temperature extreme indices. Mean: 30 yr (1975–2004) mean distribution; D2–D1: differential values between the first 2 decades (1985–1994 and 1975–1984); and D3–D2: differential values between the last 2 decades (1995–2004 and 1985–1994)

of the west coast of India is consistent with a previous study by Kaur et al. (2017), which indicated significant increasing trends in both annual and monsoon rainfall for the period 1961–2013.

3.2. Changes in temperature extremes

Spatial maps of selected key temperature extreme indices are presented in Fig. 6, where a 30 yr mean value map and 2 maps of the differential values between consecutive 10 yr mean extremes are listed for each index. The maps show substantial, and spatially coherent, trends in indices corresponding to a warming trend in the region. The warm spell duration, growing season length and the frequency of hot days and hot nights have greatly increased, while the cold spell duration and the frequency of frost nights have largely decreased. Both changes are persistent during the 3 decades in general, except for the cold spell duration index, which shows a cooling trend in first 2-decadal change map. The trends in cold spell duration are also smaller than the trends in warm spell duration. The spatial distribution of the linear trend slope for the selected indices are shown in Fig. 7, where increasing or decreasing trends at a specific location (within a 25 × 25 km pixel) are further demonstrated by time series plots. Temperature extremes represent a more systematic and spatially coherent change tendency, while there is still considerable spatial variations thanks to impressively distinct terrains in the region. Almost all temperature indices point to a rapid warming in the Himalayan range and Tibetan Plateau, except in the border region of Afghanistan and Pakistan. There have been overwhelming research reports that revealed a worrying changing climate in these areas. Temperatures are rising rapidly. Himalayan glaciers are retreating at a higher speed than in any other part of the world, which is causing lakes to expand and brings floods and mudflows to the plateau. Himalayan glaciers are vital for South Asian rivers, including the Indus. A rapid shrinking of glaciers poses a great threat to water supplies in the region.

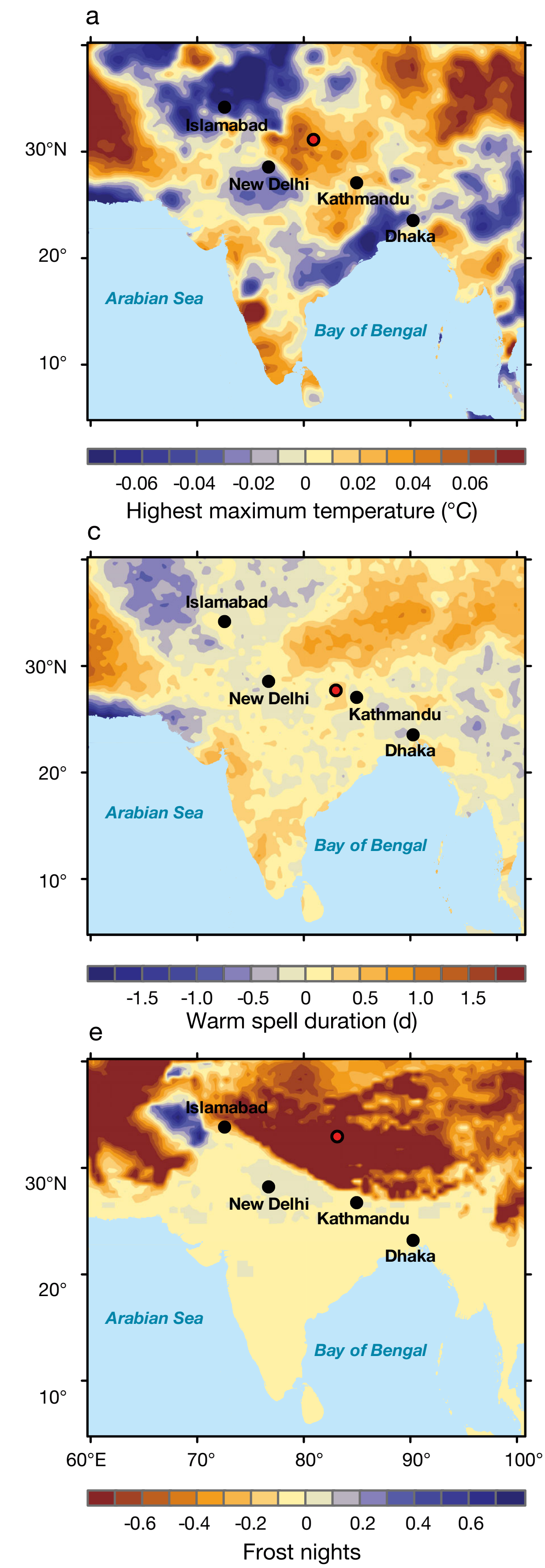
In general, regionally averaged mean temperature indices show a progressive increase in the majority of areas, except for some declines in highest maximum temperature. The overall increasing trend in Nepal, with the greatest increase being over the higher Himalayan Mountains, was also documented by Rajbhandari et al. (2017), reflecting a faster warming phenomenon in high-altitude mountains such as in the Hindu Kush-Himalaya and surrounding areas (Shrestha et al. 1999, Guo et al. 2016, Yan et al. 2016). In contrast, the negative trend in the plains near the Bay of Bengal can be explained by the presence of fog episodes adjacent to ocean regions in winter (Ross et al. 2018). These have become more frequent over the past decade, sometimes lasting for more than 1 wk or even 1 mo, which reduced the maximum temperature markedly (Shrestha et al. 2017). Ji et al. (2015) considered that such a temperature drop in the plains could be due to increased haze occurrence and its dimming effect. It should be noted that the Bay of Bengal surface temperature is regarded as the major driver of rainfall variability in northeast India (Nair et al. 2018).

Changes in the warm spell duration index follow a similar pattern to the highest maximum temperature index. The largest trends are substantial increases in the annual number of days over the region, in particular the high-altitude areas, with slight decreases confined to small areas. Warming in mountainous regions is most probably due to the contribution of increases in anthropogenic greenhouse gas emissions and changes in cloud cover amounts (You et al. 2008). The continuous warming that is exhibited in urban areas can have a huge impact on the quality of life and even on human life. The rising heat wave frequency is responsible for a large proportion of the casualties related to climate extreme. This can also result in increased disease prevalence, adversely affecting crop production, and increases in crop water requirements, as well as in domestic and industrial water use.

Several studies have been carried out on climate changes in the Himalayan region based on observed data (Hingane et al. 1985, Baidya et al. 2008, Islam et al. 2009, Shrestha et al. 2017). South Asia is experiencing fewer frosty nights than in the past. A prominent decline is found in the Himalayas. The stable growth of nocturnal temperature seen in most of Pakistan, most of India and Bangladesh is in accordance with the trend of global warming projected by the IPCC. The resultant glacial melting in the Himalayas will increase flooding and affect water resources within the next 2 to 3 decades (Barros et al. 2014).

4. CONCLUSIONS

South Asia's vulnerability to climate extremes is profound, principally for reasons related to population and poverty. Using Aphrodite-Precipitation and Princeton-Temperature data sets, which play a significant role in poorly gauged regions, we examined



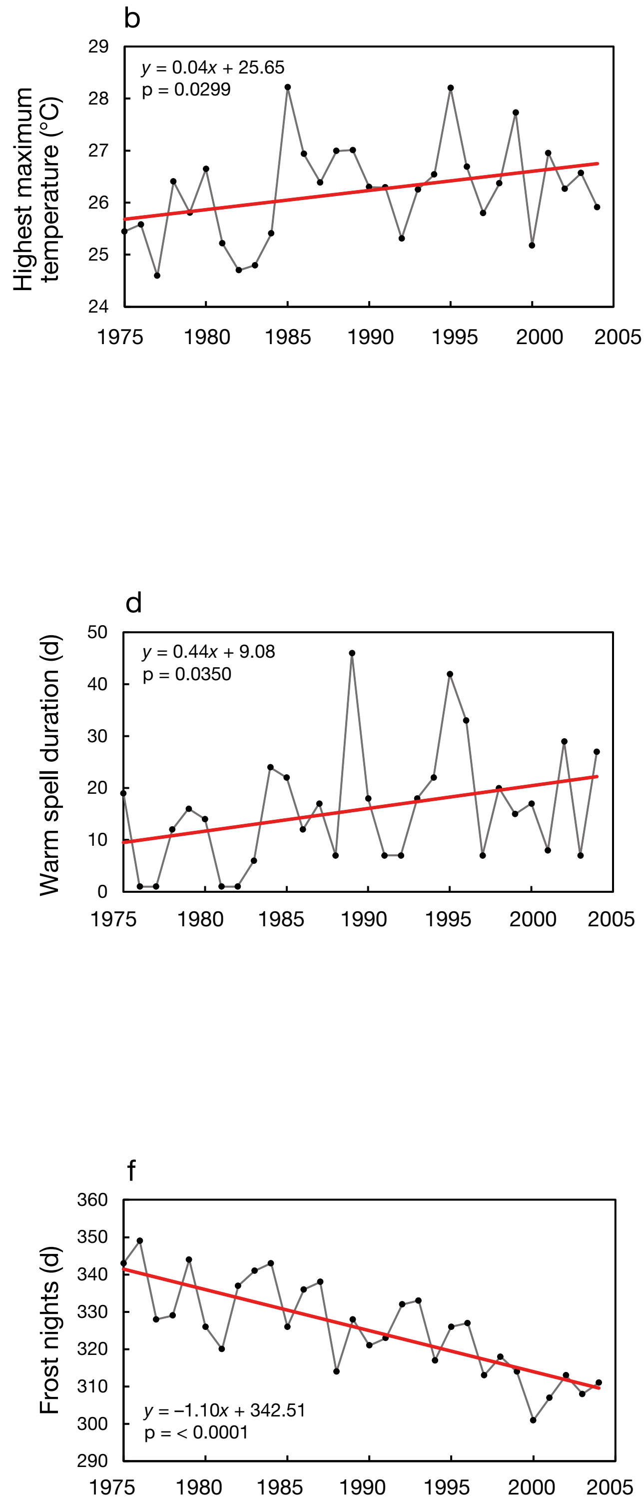


Fig. 7. (a,c,e) Spatial distribution of linear trend slope of 30 yr change in the selected key temperature indices and example locations (red dots in a,c,e). (b,d) Increasing trend; (f) decreasing trend

spatiotemporal trends in 30 indices, mainly highlighting changes in extreme climates in the South Asia region for the period 1975–2004. The derived 30 yr time series of mean annual and decadal extremes described several characteristics of extreme climates, including frequency, amplitude and persistence. Our trend slope maps estimated from these time series demonstrated the spatial distribution of their variation tendencies, and revealed local patterns of long-term change and spatial coherence among all indices over the 30 yr time span and across the whole region. The resultant gridded change trends enable more robust conclusions to be drawn, as the trends are based on spatiotemporal characteristics of changes rather than on tendencies over large areas and regionally averaged trends, as reported in previous studies. They allow world-wide compatible baseline comparisons due to the adoption of the IPCC benchmarked 30 yr period in this study.

Precipitation extremes from 1975–2004 show regional trends that agree with the average decrease in precipitation in South Asia, with very mixed spatial patterns of positive and negative trends in most extremes. Most precipitation indices present a tendency towards drier conditions coupled or associated with a faster pace of change in the last 20 years of the record. By contrast, the extreme wet day precipitation index exhibits the largest change, indicating that heavy precipitation is increasing in the region. The trend of temperature extremes shows that the region has been warming over the 3 decades studied (1975–2004). Trends for the temperature indices present a large spatial coherence, with the upward trend in the warm/hot-related indices being larger than the downward trend in cold-related indices. The highest maximum temperature extreme has also increased but to a lesser degree, which indicates more unbearable heatwaves in the region. The long-term trend for frost nights shows little change in the low-altitude southern part of the region, in particular where India, Pakistan and Bangladesh are located, though it has been decreasing since 1975.

While corresponding well to most earlier studies in the region, the spatiotemporal patterns shown in our results present a comprehensive overview of the South Asia climate extremes, which has never been revealed. The big picture is informative, and can improve our knowledge of the association between local climates and their climate-driving forces, as well the impact from climate change, and help extend research agendas to address future climate change impacts on cross-boundary (or transboundary) regional water resource planning and management. Some strong localised patterns in climate extremes exist, having the common feature of being independent from surrounding areas; e.g. all precipitation indices in Afghanistan and the highest maximum temperature index along the southwest coast of India. These patterns may be caused by insufficient data, in particular uncertainties in altitudinal precipitation extremes associated with scarcity of *in situ* observations at high elevations. These issues need to be recognised in future research.

All annual indices, together with the decadal indices and trend maps generated from them, are available. For gridded data, interested users can directly contact the corresponding authors. Relevant metadata can be obtained on request, in the form of a readme file.

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