INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2016)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.4761

Royal Meteorological Society

Observed trends and changes in daily temperature and precipitation extremes over the Koshi river basin 1975–2010

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ABSTRACT: The Koshi river basin is a sub-basin of the Ganges shared among China, Nepal, and India. The river system has a high potential for investment in hydropower development and for irrigation in downstream areas. The upper part of the basin contains a substantial reserve of freshwater in the form of snow and glaciers. Climate variability, climate change, and climate extremes might impact on these reserves, and in turn impact on systems that support livelihoods, such as agriculture, biodiversity and related ecosystem services. Climatological variability and trends over the Koshi river basin were studied using RClimDex. Daily temperature data (20 stations) and precipitation data (50 stations) from 1975 to 2010 were used in the analysis. The results show that the frequency and intensity of weather extremes are increasing. The daily maximum temperature (TXx) increased by 0.1 °C decade^{-1} on average between 1975 and 2010 and the minimum (TNn) by 0.3 °C decade^{-1}. The number of warm nights increased at all stations. Most of the extreme temperature indices showed a consistently different pattern in the mountains than in the Indo-Gangetic plains, although not all results were statistically significant. The warm days (TX90p), warm nights (TN90p), warm spell duration (WSDI), and diurnal temperature range (DTR) increased at most of the mountain stations; whereas monthly maximum and minimum values of daily maximum temperature, TX90p, cool nights (TN10p), WSDI, cold spell duration indicator (CSDI), DTR decreased at the stations in the Indo-Gangetic plains, while the number of cold days increased. There was an increase in total annual rainfall and rainfall intensity, although no clear long-term linear trend, whereas the number of consecutive dry days increased at almost all stations. The results indicate that the risk of extreme climate events over the basin is increasing, which will increase people's vulnerability and has strong policy implications.

KEY WORDS climate extremes; Koshi basin; temperature; precipitation; climate indices

Received 24 December 2014; Revised 4 April 2016; Accepted 5 April 2016

1. Introduction

For decades, global climate change studies using observational temperature and precipitation data focused only on changes in mean values and there were few studies of climate extremes. In recent decades, because the issue of climate change became more prominent, the research on past climate trends has progressed enormously, especially for precipitation and temperature (Manton *et al.*, 2001; Frich *et al.*, 2002; Alexander *et al.*, 2006; Klein Tank *et al.*, 2006; Donat *et al.*, 2013; Whan *et al.*, 2013). The Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) highlighted the fact that insufficient studies were available on observed historical trends in climate extremes, and suggested that more studies would give a clearer indication of what changes might already have occurred in the global climate (Nicholls *et al.*, 1996). At the time it was already envisaged that one of the effects of global warming might be an increase in weather and climate extremes. Studies of climate extremes are also useful for the verification of climate model results and thus increasing confidence in projections of future climate (Kruger, 2006).

Very few studies have been made of climate extremes in Nepal or the adjacent countries in the Hindu Kush Himalayan region (especially not in a basin wise context). Hingane *et al.* (1985) made a detailed study of historical time series of temperature data from India and found a definite warming trend in mean annual all India temperature with an increase of 0.4 °C over the preceding century. Shrestha *et al.* (1999) analysed the trend in maximum temperature in Nepal and found an average annual warming of 0.06 °C year^{-1} between 1971 and 1994. The increase in maximum temperature was more pronounced in the high-altitude regions. Some results indicate the importance of spatial variation. An analysis of climate changes in the Nepalese part of the Koshi river basin showed a significant increase in temperature and precipitation in a few of the areas within the basin,

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decreasing trends in a very few areas, but no trends at most stations (Sharma *et al.*, 2000). A study by Islam (2009) showed that wet days over Nepal are increasing; consecutive dry days, monthly maximum 1-day precipitation, and monthly maximum consecutive 5-day precipitation are decreasing; maximum and minimum temperatures are increasing; the number of cool days and cool nights is decreasing, and the number of warm nights is increasing. Baidya *et al.* (2008) also observed an increasing trend in temperature and precipitation extremes over Nepal. A study done by Caesar *et al.* (2011) considering seven stations from Nepal (among those three stations from Koshi river basin) showed that warm extremes are increasing and cold extremes are decreasing. They found that trends in precipitation extremes are less spatially consistent across the region. You *et al.* (2008) assessed the changes in daily climate extremes in the eastern central Tibetan Plateau during 1961–2005 and found large proportion of stations showing statically significant trends for all temperature indices with decrease in extreme cold days/nights together with increase in extreme warm days/nights. While most precipitation indices show increasing trends in the southern and northern Tibetan Plateau and show decreasing trends in the central Tibetan Plateau. Manton *et al.* (2001) assessed trends in extreme daily rainfall and temperature in Southeast Asia from 1961 to 1998 and found a significant increase in annual hot days and warm nights, a significant decrease in cool days and cold nights, a significant decrease in the number of rainy days across the region, and at many stations an increase in the proportion of annual rainfall from extreme events. Klein Tank *et al.* (2006) investigated the changes in daily temperature and precipitation extremes in central and south Asia from 1961 to 2000. They found a significant increase in the percentage of warm nights and days and a decrease in the percentage of cold nights and days at 70% of stations; the daytime trends in maximum temperature extremes were smaller than the night-time trends in minimum temperature extremes. There was no consistent pattern of change in precipitation extremes, but there was a significant increase in extreme precipitation indices. Singh *et al.* (2014) assessed extreme wet and dry spells over the core region during the South Asia summer monsoon season from 1951 to 2011 and found a significant increase in the frequency, but decrease in intensity, of dry spells, and a significant increase in the intensity of wet spells. Donat *et al.* (2013) analysed temperature and precipitation extreme indices from 1901 to 2010 on a global scale. Their main findings included widespread and significant warming trends related to temperature extremes, mostly stronger for indices based on daily minimum temperatures than for indices calculated from daily maximum temperatures. The changes in precipitation extremes were in general spatially more complex and locally less significant. However, on a global scale, there was a tendency towards wetter conditions for most precipitation indices, i.e. the intensity, frequency, and duration of extreme precipitation is increasing on average.

Changes in the frequency and intensity of extreme climate events are likely to have an immediate and intense impact on society and the environment, and climate change is likely to exacerbate any existing problems in a river basin. The Koshi river basin has been selected as a key river basin for studies to improve understanding of changes and trends in climate indices. In the following, we describe the results of a study of spatial and temporal differences and trends in climate extremes over the Koshi river basin using RClimDex software. The study provides a comprehensive analysis of observed temperature and precipitation extremes over the whole basin, including some stations in parts of the basin in China (Tibet Autonomous Region), Nepal and India; and includes data and information differentiated by elevation.

2. Methods and data

2.1. Study area

The Koshi river originates in the high-altitude Tibetan Plateau and flows through the Himalayan range, the headwater area for a number of major tributaries, and Nepal's mid-mountains to the Terai lowland region in Nepal and India, where it joins the Ganges (Figure 1). A vast alluvial fan has developed over the centuries along the plains reaches of the river. The basin drains an area of some 87 970 km^2; approximately 32% in China, 45% in Nepal, and 23% in India. The elevation range within the basin is extreme, extending from the highest point in the world, 8848 masl at the summit of Mount Everest, to just over 30 masl in the plains. The population density ranges from less than 4 people per square kilometre in the northern portion to more than 1000 people per square kilometre in the plains.

The region includes five climatic zones determined mainly by elevation (Khanal *et al.*, 2007) (Figure 1) and has nine distinct eco-regions. The vegetation is influenced by differences in soil, topography, and climate and varies greatly across the regions from deciduous forest in the tropical and subtropical region, through mixed forest in the temperate zones and alpine forest in the sub-alpine zone, to the rangelands and grassland of the high mountains. The extreme changes in elevation in the mountain area from high peaks to deep valleys means that there can be a great variation of vegetation within the different physiographic zones (Shrestha and Devkota, 2010).

The climate in the basin varies from humid tropical in the south, through subtropical and temperate, to cold and arid in the north. The climate in the southern part of the basin is strongly influenced by the South Asian monsoon, whereas to the north the Tibetan plateau lies in a rain shadow area.

The annual precipitation ranges from 207 mm in the trans-Himalaya to more than 3000 mm in the eastern mountains and mid-mountains of Nepal (Neupane *et al.*, 2013). Precipitation patterns in the basin are directly associated with the summer monsoon, with about 80% of the annual precipitation falling between June and September. Owing to the great variation in topography, the spatial and

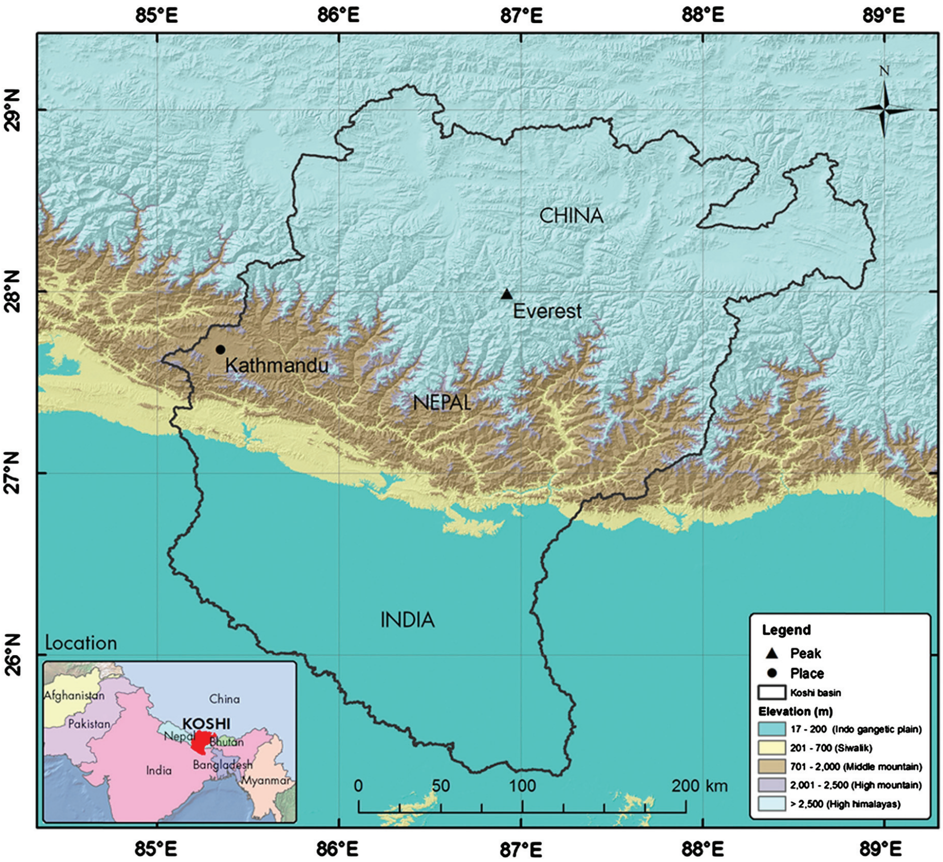

Figure 1. Location of the Koshi river basin.

temporal complexity of rainfall is large within short distances. In the temperate region there is a clear correlation between land elevation and precipitation.

The Koshi river system has a high potential for investment in hydropower development as well as irrigation in the downstream areas. In addition, the basin contains important ecosystems and protected areas that support a high level of biodiversity and provide a range of ecosystem services that sustain livelihoods. However, the diverse topography, young geological formation, high degree of glaciation, and strong monsoon influence make the basin particularly prone to erosion and sedimentation and natural hazards such as glacial lake outburst floods (GLOF), flash and riverine floods, landslides, debris flows, and drought (Shrestha *et al.*, 2010). Poor women and men are the most vulnerable and hardest hit by natural hazards, and it is thought that the hazards may increase in magnitude and frequency with climate change (Goswami *et al.*, 2006). Increasing population, urbanization, natural resource degradation, and encroachment have also added pressures on the freshwater ecosystems of the Koshi basin. The livelihoods of a large part of the rural population, and especially the poor, depend on the Koshi basin's ecosystem services and arable land. Neupane *et al.* (2013) suggested climate change is likely to lead to an increase in water scarcity in the basin, which will ultimately influence the agro-based livelihoods of the basin population and threaten food security.

2.2. Data

Daily precipitation and temperature (both maximum and minimum) values for all available gauges within the Nepal portion of the Koshi basin were acquired from the Department of Hydrology and Meteorology (DHM) of Nepal. Data for two stations in Tibet Autonomous Region, China – Nielamu and Dingri – were provided by the Tibetan Meteorological Bureau. Data for the Indian part of the basin were extracted from the $1° \times 1°$ India Meteorological Department (IMD) grid dataset (Rajeevan *et al.*, 2005; Srivastava *et al.*, 2009). In all, precipitation data was obtained from 73 stations and temperature data from 36 stations. In addition six IMD grid points were used. Following screening for data quality (see below), 50 stations were selected to provide daily precipitation data for the study; and 20 stations to provide daily temperature data (Figure 2).

Studies of climate change require a long period of data in order to identify long-term trends rather than short-term fluctuations (WMO, 1996). Temperature and precipitation data were obtained for a period of 35 years from 1975 to 2010. The aim was to encompass all the climatic zones in the Koshi basin. This could not be completely achieved due to the complex topography of the basin and the limited number of stations available, but spatial coverage was increased by including nearby stations from areas just beyond the basin boundary (Figure 2). The 50 stations that provided precipitation data lay at elevations

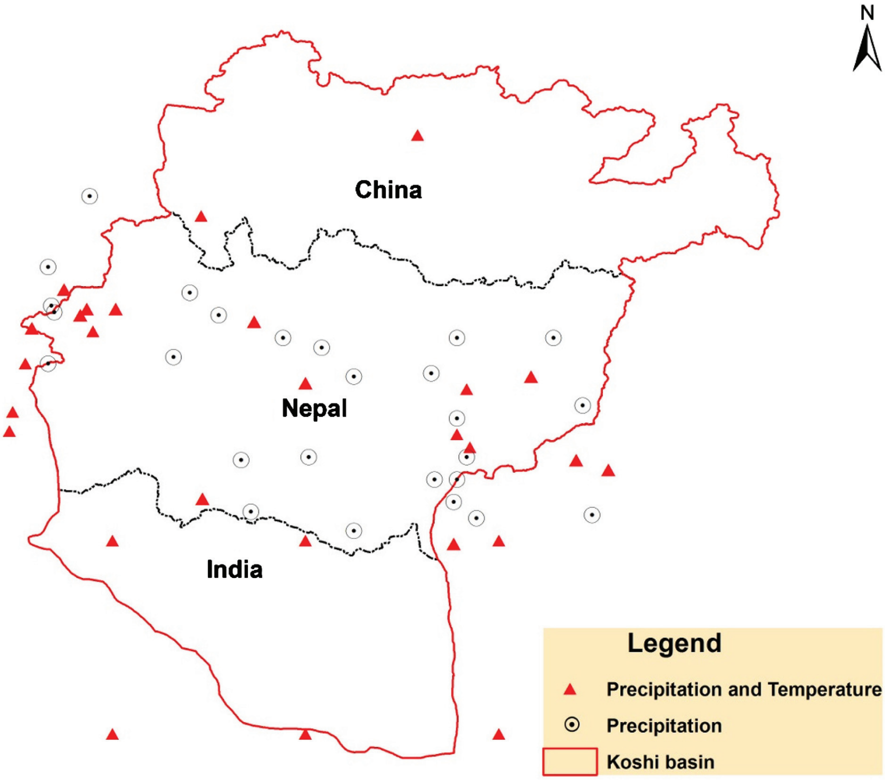

Figure 2. Location of the stations used in the study.

from 33 to 4300 masl. Of the 20 stations that provided temperature data, six were located in the high hills and mountains above 2000 masl; six in the hill region at elevations between 1300 m and 1750 masl, and eight in the Indo-Gangetic plains at elevations below 91 m. To capture the different topography or climatology diversity of the basin we divided the stations into five sub-division High Himalaya (HH); High Mountain (HM); Middle Mountain (MM); Siwalik (S); Indo-Gangetic Plain (IG) (Tables 3 and 4, Figures 1, 5 – 10 and 12 – 14).

2.3. Quality control and homogenization

One of the most important steps in the study was to ensure the quality and completeness of the data. Stations with only a short period of data records or more than 5% of data missing were discarded. The precipitation and temperature data underwent several steps of screening using visual checks of data plots using MS Excel and RClimDex for erroneous outliers. The computer program RClimDex identifies erroneous temperature and precipitation data on a first run, such as daily precipitation amounts less than 0 mm or days with T_{max} less than T_{min}. Second step identifies outliers in daily maximum and minimum temperature, which have to be manually checked, validate, corrected by looking tempQC.cvs, prcpQC.cvs, and tepstdQC.cvs in a subdirectory called log. For temperature, they are defined as daily values outlying a user-defined threshold determined by mean ± SD. In our case, we choose four standard deviations as the thresholds for a finer quality control of the data. Both for precipitation and temperature, data plots are available for visual inspections to reveal more outliers as well as a variety of problems that cause changes in the seasonal cycle or variance of the data in a same subdirectory plot. For precipitation histograms of the data are created which reveal problems that show up when looking at whole data (You *et al.*, 2008).

The next step was to test the homogeneity of the data series. A homogeneous climate time series is defined as one in which variations are caused only by variations in climate and not, for example, by changes in station location, observation procedures and practice, or instrumentation (Aguilar *et al.*, 2003, 2005). The purpose of homogeneity test is to remove the non-climate factors from the data as much as possible before the climate data can be reliably used for climate change study. The RHtest software package was applied to data for homogeneity testing because it can be used without reference series and freely available. RHtest can help to identify step changes in a time series by comparing the goodness of fit of a two phase regression model with that of a linear trend for the entire series. It is used to help identify sudden jumps (change points) in indices of temperature and precipitation data. As done by Caesar *et al.* (2011) we did not attempt to adjust the data as a result of the homogeneity tests and excluded the data that appear to be potentially suspect.

Homogeneity assessment and adjustment can be quite complex and it often requires close neighbour stations, detailed station history and a great amount of time (Vincent *et al.*, 2005).

But this is often not possible due to the sparseness of the station network. In this study, we considered stations

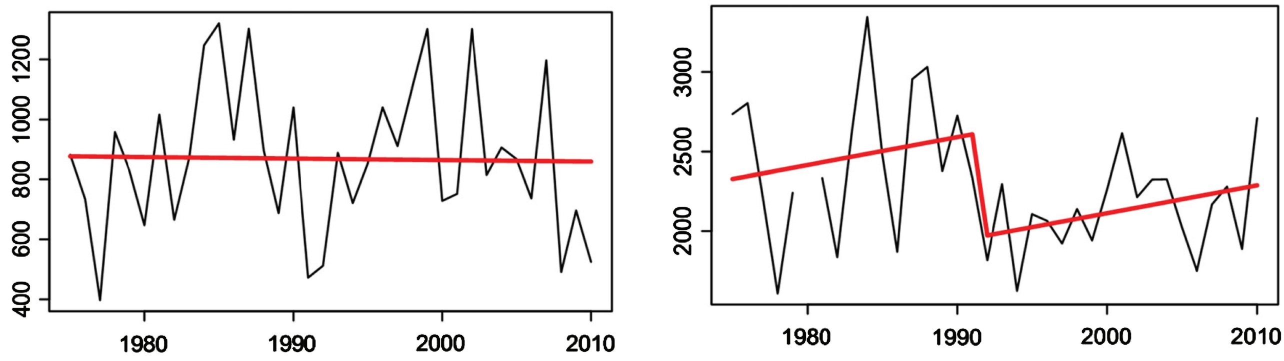

Figure 3. RClimDex RHtest results for data homogeneity. (a) Homogeneous precipitation data series with no significant break point; (b) non-homogeneous precipitation data series with significant break point.

individually without using a reference series, as suitable reference series were unavailable due to lack of homogeneous series data, lack of proper metadata and very scattered spatial distribution of stations and use only *F* tests. *F* tests allows the time series being tested to have a linear trend throughout the whole period of data record (means no shift in the trend component), with the annual cycle, linear trend and lag-1 autocorrelation of the base series being estimated in tandem through iterative procedures, while accounting for all the identified mean shifts (Wang, 2008). More details on RHtest is given in *RHtestsV3 User Manual* (Wang and Feng, 2010) and in Whan *et al.* (2013), Caesar *et al.* (2011), Klein Tank *et al.* (2009), You *et al.* (2008).

Figure 3 shows an example of homogeneity testing of precipitation data from stations SI1115 and SI1016. The values for SI1115 (a) show no sudden jumps in the data series whereas those for SI1016 (b) show a sudden jump after 1990. Tests using the *F*-test showed that the jumps were significant. Stations that showed significant jumps (significant change points) of this type were rejected, and the data were not used.

After data quality control and homogeneity assessment; 20 stations were left for analysis of temperature indices (from maximum and minimum temperature) and 50 stations were left for analysis of precipitation indices (Tables 3 and 4). For the indices calculation in RClimdex, upper and lower threshold values were defined for daily maximum and minimum temperatures, and user define daily precipitation threshold for rainfall. An average temperatures of MAM (March, April, May) were taken for upper threshold of daily maximum temperature and an average temperatures of DJF (December, January, February) were taken for upper threshold of daily minimum temperature and an average of daily rainfalls from JJAS (June, July, August, September) were taken for user define daily precipitation threshold based on the historically observed data (1975–2010; Islam, 2009).

2.4. Trend and indices analysis

The long-term trends were analysed using simple linear regression (Wang and Feng, 2010), and significance was analysed using Student's *t*-test (Miller and Miller, 1988). Daily temperature and precipitation data were used to calculate extreme climate change indices using the specially designed software RClimDex (1.0) (http://cccma.seos.uvic.ca/ETCCDI/RClimDex/rclimdex.r). RClimDex (1.0) is a freely available tool designed to provide a user friendly interface to compute indices of climate extremes and runs under the R programming environment (http://www.r-project.org/). RClimDex has become a standard tool for developing climate change indices and has been used by many authors, for example Baidya *et al.* (2008), Islam (2009), Whan *et al.* (2013), Alexander *et al.* (2006), State and Service (2008), Manton *et al.* (2001), Klein Tank *et al.* (2006), and Donat *et al.* (2013). RClimDex performs in the R Console and includes a data quality control procedure before computing the indices (see above). It computes 27 core indices (11 for precipitation and 16 for temperature) recommended by the Commission for Climatology (CCl), World Climate Research Programme (WCRP) of the Climate Variability and Predictability Component (CLIVAR) project and Expert Team for Climate Change Detection and Indices (ETCCDI). Of the 27 indices, 23 are relevant for the region and were selected for the study (Table 1).

2.5. Comparison of observed data with $1° \times 1°$ IMD grid dataset

Owing to limited availability or access of observed historical meteorological data from Indian part of Koshi basin, $1° \times 1°$ IMD grid dataset were used for climate indices analysis (Tables 3 and 4). The study from King *et al.* (2013) indicates that in general gridded datasets are suitable for investigating extreme rainfall trends and variability, but suggest that the data should be first validated and correlated. This is particularly important as rest of the data are station based. For the validity of the $1° \times 1°$ IMD grid dataset, the gridded data was compared with few available observed station data from Bihar, India (Figure 4). For this, grid point X85.5, Y25.5 was compared with Patna station, X85.5, Y26.5 was compared with Buchana station, X86.5, Y25.5 was compared with Bhagalpur station and X87.5, Y25.5 was compared with Sabour station.

The results show that almost all climate indices generated by IMD grid data follow the same trend and sign as observed station data but only few threshold indices

Table 1. ETCCDI recommended climate indices used in the study.

ID	Indicator name	Definition	Unit
TXx	Max. T_{max}	Monthly maximum value of daily maximum temp	°C
TNx	Max. T_{min}	Monthly maximum value of daily minimum temp	°C
TXn	Min. T_{max}	Monthly minimum value of daily maximum temp	°C
TNn	Min. T_{min}	Monthly minimum value of daily minimum temp	°C
TN10p	Cool nights	Percentage of days when TN < 10th percentile	%
TX10p	Cool days	Percentage of days when TX < 10th percentile	%
TN90p	Warm nights	Percentage of days when TN > 90th percentile	%
TX90p	Warm days	Percentage of days when TX > 90th percentile	%
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX > 90th percentile	%
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN < 10th percentile	%
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C
RX1day	Max. 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
Rx5day	Max. 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP ≥ 1.0 mm) in the year	mm/day
R10	Number of heavy precipitation days	Annual count of days when PRCP ≥ 10 mm	Days
R20	Number of very heavy precipitation days	Annual count of days when PRCP ≥ 20 mm	Days
Rnn	Number of days above nn (50, 100, 150) mm	Annual count of days when PRCP ≥ nn mm, nn is user defined threshold	Days
CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR ≥ 1 mm	Days
R95p	Very wet days	Annual total PRCP when RR > 95th percentile	mm
R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR ≥ 1 mm)	mm

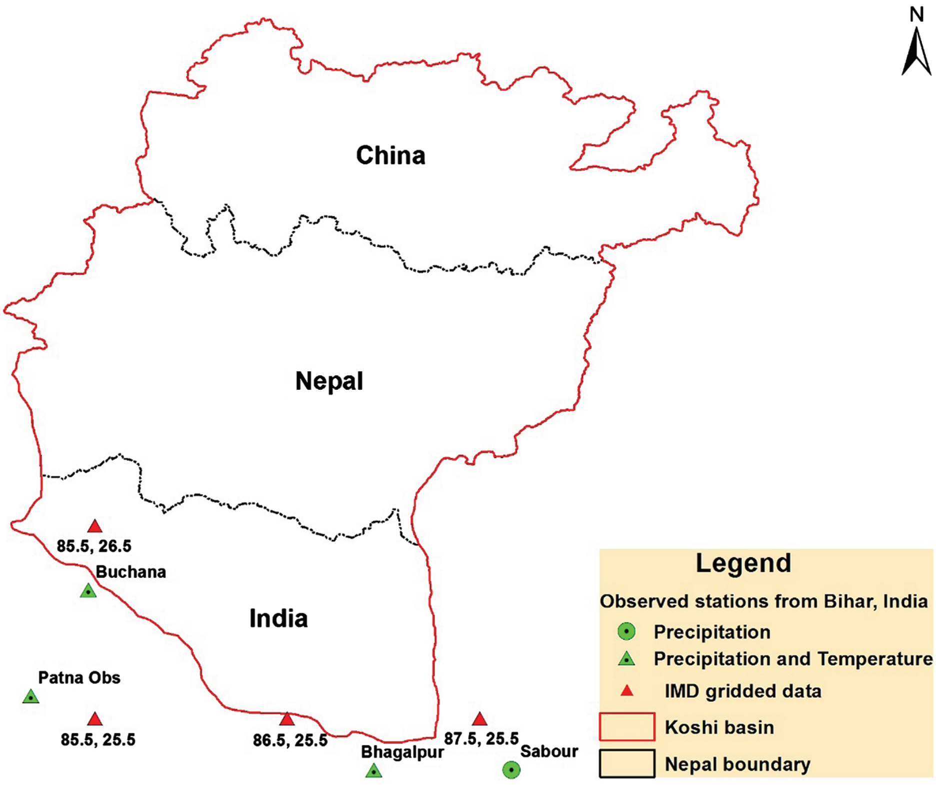

Figure 4. The stations used to compare observed station data with 1° × 1° IMD grid dataset in Koshi India part.

Table 2. Comparison of observed stations with IMD grids.

Indices	Units	Patna station	X85.5, Y25.5 (IMD grid)	Sabour station	X87.5, Y25.5 (IMD grid)	Bhagalpur station	X86.5, Y25.5 (IMD grid)	Buchana station	X85.5, Y26.5 (IMD grid)
TXx	°C	−0.005	−0.042			−0.015	−0.039	0.035	−0.026
TXn	°C	−0.04	−0.032			−0.094	−0.063	−0.114	−0.061
TNx	°C	0.009	0.001			0.028	0.029	0.021	0.027
TNn	°C	−0.015	−0.014			−0.023	0.003	0.032	0.003
TX10p	%	0.025	0.023						
TX90p	%	0.007	−0.07						
TN10p	%	−0.158	−0.214						
TN90p	%	0.24	0.151						
WSDI	%	0.148	0.007						
CSDI	%	−0.076	−0.049						
DTR	°C	−0.027	−0.022			−0.094	−0.041	−0.032	−0.04
Rx1day	mm	−0.545	−0.954	1.066	3.456	0.515	2.327	−4.39	1.11
Rx5day	mm	−1.207	−1.012	2.016	5.527	0.831	6.096	−5.262	−1.973
SDII	mm	−0.042	0.014	0.106	0.105	0.103	0.199	−0.623	−0.137
R10mm	Days	−0.079	0.014	0.048	0.481	−0.14	0.594	−0.308	0.282
R20mm	Days	−0.1	0.085	0.041	0.163	−0.055	0.507	−0.427	−0.009
R50mm	Days	−0.079	−0.024	0.082	0.147	0.026	0.154	−0.177	−0.098
CDD	Days	1.656	0.256	1.302	1.033	3.287	0.909	1.529	0.05
CWD	Days	0.003	0.015	0.121	0.128	−0.014	0.121	0.049	0.085
R95p	mm	−3.687	−2.26	8.277	14.052	3.461	15.289	−17.238	−5.613
R99p	mm	−1.295	−2.477	3.154	9.347	3.042	10.258	−11.606	0.347
PRCPTOT	mm	−6.136	−1.663	7.115	19.056	−1.066	26.147	−25.39	1.676

Start and end year are different for different stations: Patna (1975–2009), Sabour (1975–2005), Bhagalpur (1975–2009) and Buchana (1982–2007). But except Patna there are lots of no data in the remaining three stations.

(R10mm, R20mm) and SDII showed slightly difference (Table 2). Time series comparison of indices at Biratnagar and Patna with corresponding grid points do not show temporal divergence in the value (not shown due to lack of space) indicating that the gridded data represent the observation adequately. The correlation coefficient between gridded datasets and stations were more than 0.9 in minimum and maximum temperature but less than 0.5 regarding the rainfall. From this we concluded that, while there was an overall reduction in the number of stations contributing to the Indian gridded dataset, there were no significant changes in the network density in the study region until the end of the study period and therefore the IMD grid data captures the climatology of the lower basin.

3. Results and discussion

3.1. Seasonal temperature trends

The long-term (1975–2010) trends in seasonal maximum and minimum temperatures are shown in Figures 5 and 6. The maximum (Figure 5) and minimum (Figure 6) seasonal temperatures showed an increasing trend at the majority of stations and most of the values were statistically significant at a 95% significance level. Ji and Kang (2014) highlighted that changes in extreme temperature become increasingly pronounced from South to North China, with the most significant changes occurring on the Tibetan Plateau. The few decreasing trends were mostly not statistically significant except in the IGs, where the maximum seasonal temperature showed a decreasing trend in all seasons except the monsoon, although the decrease was only statistically significant in winter and pre-monsoon, which is consistent with the results reported by Ji *et al.* (2015). At most stations maximum seasonal temperatures had increased at a rate of more than 0.3 °C decade^{-1}. The increases in seasonal minimum temperature were generally higher than those in seasonal maximum temperature, which is consistent with the results reported by Alexander *et al.* (2006). There was no conspicuous difference in the change in minimum seasonal temperatures between the plains and the mountains, with increases observed at almost all stations. The rate of increase in minimum seasonal temperature was somewhat higher in winter than in other seasons, and more often statistically significant, which is consistent with the results reported by Donat *et al.* (2013). Overall, the results showed widespread significant changes in temperature trends consistent with warming, especially for those indices derived from daily minimum temperature, with stronger trends in more recent decades.

3.2. Temperature indices

The trends in temperature indices derived from the maximum and minimum daily temperatures are shown in Table 3 and those are arithmetic mean of the values of the 20 stations used in this study. The monthly maximum value of daily maximum temperatures (TXx) increased on average by 0.1 °C decade^{-1}. Six of the 20 stations showed a statistically significant increase and four (all in the IGs) a statistically significant decrease. The monthly maximum value of daily minimum temperatures (TNx) increased on average by 0.2 °C decade^{-1}; 14 of the 20 stations showed an increase (nine statistically significant). The monthly

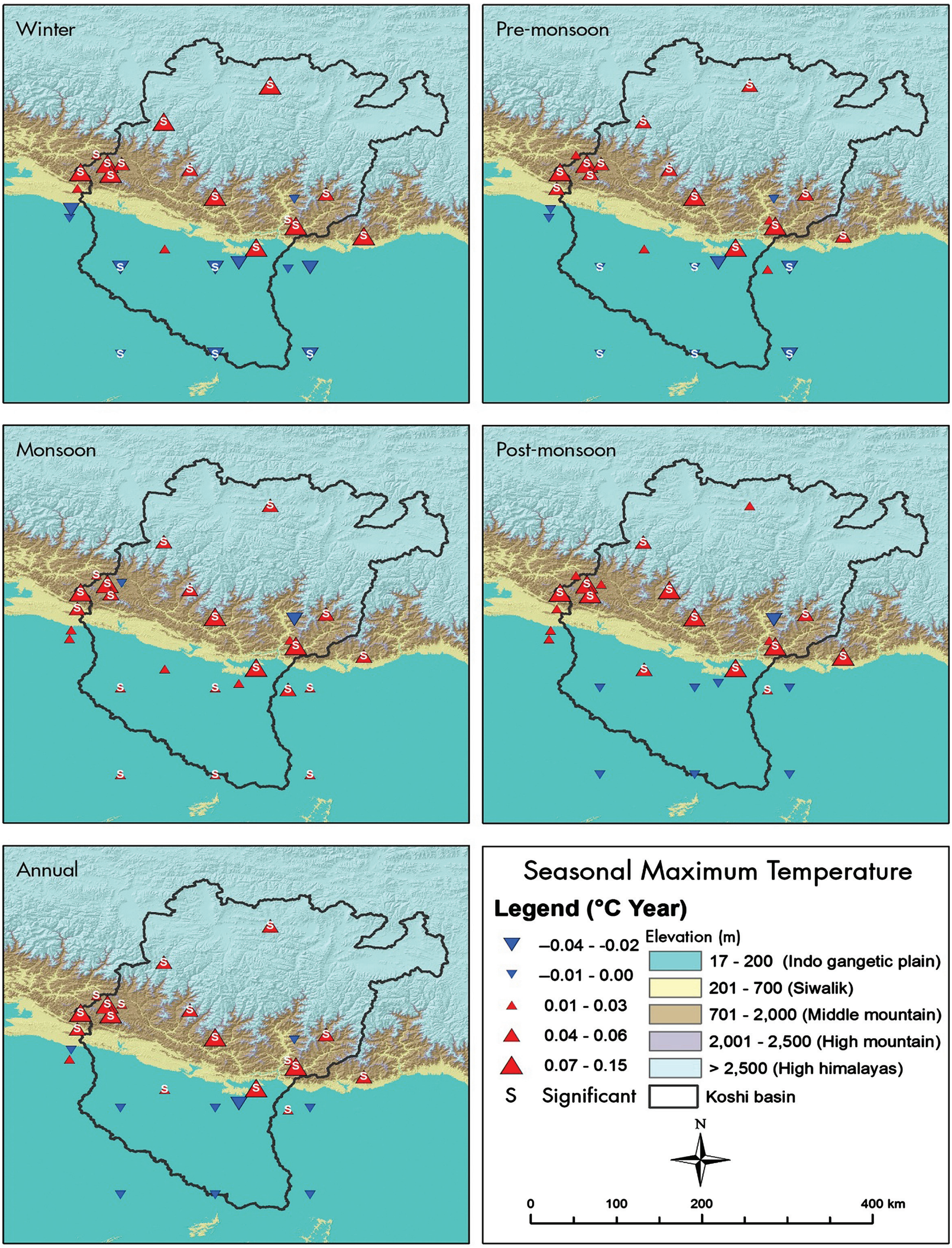

Figure 5. Trends in maximum seasonal temperature for 1975–2010: (a) winter (DJF); (b) pre-monsoon (MAM); (c) monsoon (JJAS); (d) post-monsoon (ON); (e) annual.

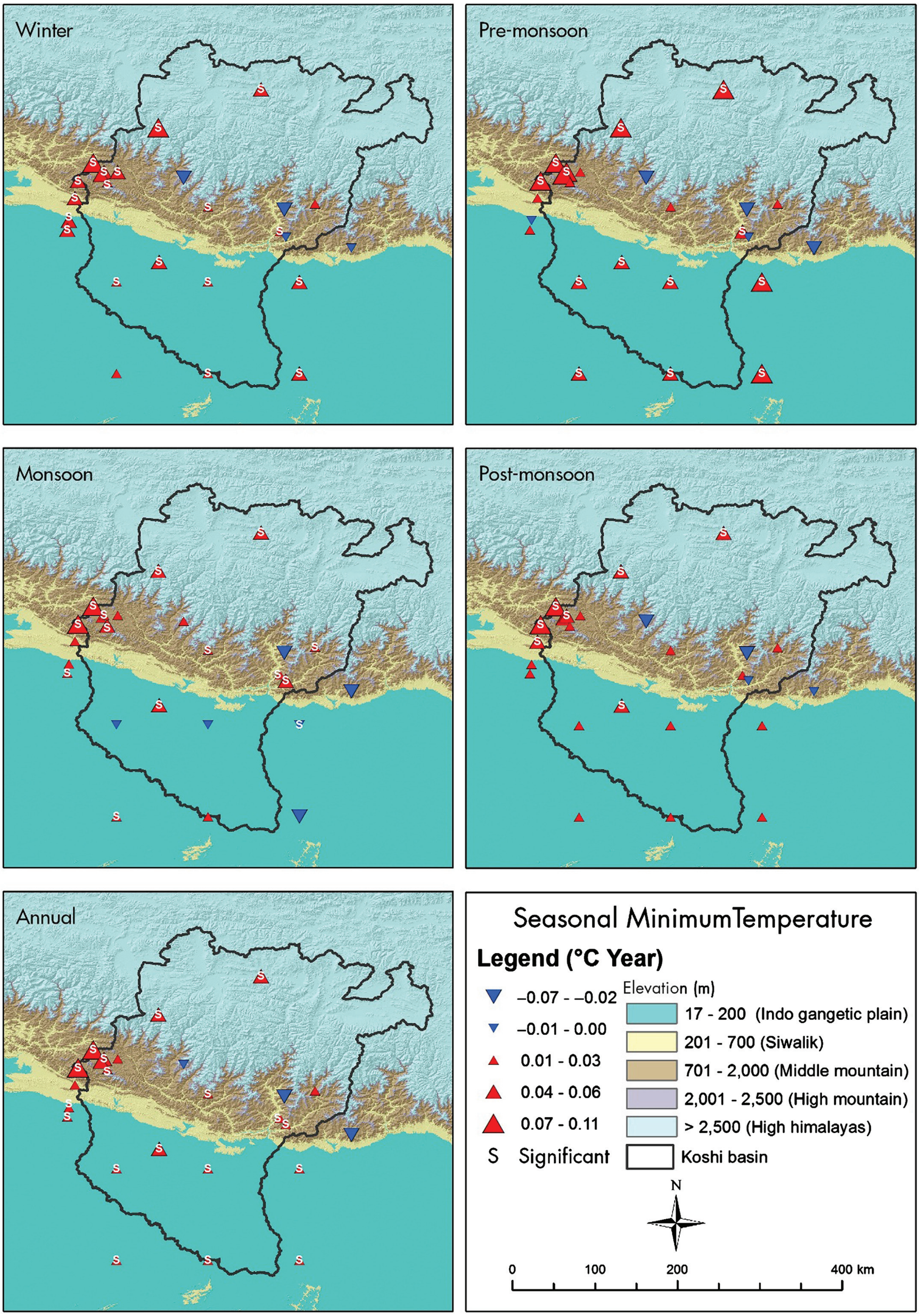

Figure 6. Trends in minimum seasonal temperature for 1975–2010: (a) winter (DJF); (b) pre-monsoon (MAM); (c) monsoon (JJAS); (d) post-monsoon (ON); (e) annual.

Table 3. Trends in annual temperature indices over the Koshi basin (1975–2010).

StnIndex	Lat. (DD)	Long. (DD)	Elev. (m)	TXx	TXn	TNx	TNn	TX10p	TX90p	TN10p	TN90p	WSDI	CSDI	DTR
S55655 (China)	28.60	87.06	4300 (HH)	0.02	**0.12**	**0.02**	**0.08**	**−0.30**	**0.32**	**−0.50**	**0.53**	**0.51**	**−0.21**	−0.01
S55664 (China)	28.18	85.96	3310 (HH)	0.01	**0.08**	**0.02**	**0.08**	**−0.29**	**0.47**	**−0.50**	**0.53**	**0.61**	**−0.21**	0.01
SI905 (Nepal)	27.60	85.08	2314 (HM)	**0.07**	0.05	**0.12**	0.00	−0.11	**1.59**	−0.03	**1.00**	**3.52**	0.10	0.03
SI1043 (Nepal)	27.70	85.52	2163 (HM)	0.00	0.03	−0.01	**0.05**	0.00	0.36	0.12	0.50	0.02	0.07	0.00
SI1007 (Nepal)	27.80	85.25	2064 (HM)	**0.05**	0.04	**0.05**	**0.15**	0.11	**0.40**	**−0.20**	**1.50**	**0.56**	**−0.34**	**−0.06**
SI1103 (Nepal)	27.63	86.23	2003 (HM)	**0.05**	0.03	−0.01	−0.02	**−0.10**	**1.22**	**0.43**	**0.21**	**2.47**	0.38	**0.08**
SI1405 (Nepal)	27.35	87.67	1732 (MM)	**0.05**	**0.08**	−0.01	−0.01	−0.08	**1.55**	0.07	**0.50**	**3.33**	0.05	**0.05**
SI1206 (Nepal)	27.32	86.50	1720 (MM)	**0.09**	**0.08**	0.01	0.00	−0.07	**2.16**	0.14	**0.28**	**5.21**	0.13	**0.10**
SI1416 (Nepal)	26.87	88.07	1678 (MM)	0.03	**0.10**	−0.02	0.00	**−0.11**	**1.38**	0.47	0.19	**3.08**	0.88	**0.02**
SI1029 (Nepal)	27.67	85.33	1350 (MM)	−0.01	**0.12**	−0.01	**0.06**	−0.09	**1.33**	**−0.15**	**0.50**	**3.48**	−0.09	**0.02**
SI1030 (Nepal)	27.70	85.37	1336 (MM)	**0.07**	0.02	0.01	**0.05**	−0.04	**1.73**	−0.13	**0.59**	**4.12**	−0.06	**0.04**
SI1407 (Nepal)	26.92	87.90	1300 (MM)	0.01	**0.08**	0.01	0.00	−0.06	**1.51**	**0.24**	**0.33**	**3.95**	0.18	**0.08**
SI1111 (Nepal)	26.72	85.97	90 (IG)	0.00	**−0.13**	0.02	0.03	**0.25**	**0.43**	−0.03	**0.75**	**0.50**	**−0.18**	**−0.03**
X875Y265 (India)	26.50	87.50	79 (IG)	**−0.04**	**−0.06**	**0.04**	0.03	0.06	−0.05	−0.39	**0.62**	−0.15	−0.20	**−0.04**
X865Y265 (India)	26.50	86.50	77 (IG)	−0.03	**−0.07**	**0.04**	0.00	0.06	−0.04	**−0.42**	**0.58**	−0.04	−0.36	**−0.05**
SI1319 (Nepal)	26.48	87.27	72 (IG)	0.00	−0.08	−0.02	0.03	**0.22**	**0.66**	−0.03	**0.57**	**0.87**	−0.08	−0.01
X855Y265 (India)	26.50	85.50	63 (IG)	−0.03	**−0.06**	**0.03**	0.00	0.05	−0.02	**−0.37**	**0.53**	−0.08	−0.22	**−0.04**
X855Y255 (India)	25.50	85.50	50 (IG)	**−0.04**	−0.03	0.00	0.01	0.02	−0.07	−0.21	0.15	−0.01	−0.05	−0.02
X865Y255 (India)	25.50	86.50	39 (IG)	**−0.04**	**−0.06**	**0.03**	0.00	0.08	−0.07	**−0.43**	**0.50**	−0.16	−0.10	**−0.04**
X875Y255 (India)	25.50	87.50	33 (IG)	**−0.05**	**−0.07**	**0.04**	0.02	0.11	−0.14	−0.55	**0.55**	−0.30	−0.43	**−0.06**
Average				0.01	0.01	0.02	0.03	−0.01	0.74	−0.12	0.55	1.57	−0.04	0.00
Stations with + positive trend				11	12	14	18	10	14	6	20	14	7	10
Stations with negative trend				8	8	6	2	10	6	14	0	6	13	10
Stations with 0 trend				1	0	0	0	0	0	0	0	0	0	0

Bold indicates statistically significant at 5%.

minimum value of minimum temperature (TNn) increased on average at a rate of 0.3 °C decade^{-1}; 18 of the 20 stations showed an increase (six statistically significant). This finding is consistent with previous study done by Liu *et al.* (2006) over the eastern and central Tibetan Plateau during 1961–2003. The monthly minimum value of daily maximum temperature (TXn) increased on average at a rate of 0.1 °C decade^{-1}; 12 of the 20 stations showed an increase (seven statistically significant), and eight, all in the IGs, a decrease (six statistically significant) (Figure 7). Baidya *et al.* (2008) suggested that the negative trend in TXn in the plains might be the result of the fog episodes in winter which have become more frequent over the past decade, sometimes lasting for more than a week or even a month, which reduced the maximum temperature significantly. A study done by Ji *et al.* (2011) shows that negative trend in TXn in the plains could be due to emission of anthropogenic particles such as sulphate and organic carbon which scatter the incoming solar radiation and reduction in the radiative forcing causing the decrease of temperature in IGs and another study by Ji *et al.* (2015) shows that negative trend in TXn in the plains could be due to increased haze occurrence and its dimming effect. Similarly, You *et al.* (2008) suggested that warming in the MM, HM and HH most probably due to the increase in anthropogenic greenhouse gases emission contributing and change in cloud cover.

The number of warm days, i.e. days in which the daily maximum temperature was above the 90th percentile (TX90p), increased at all 12 hill stations and 2 of the 8 stations in the plains, with the increase statistically significant at 13 stations; it decreased at the remaining 6 stations in the plains, although the decrease was not statistically significant (Figure 8). The number of cool days, i.e. days in which the daily maximum temperature was below the 10th percentile (TX10p), decreased at 10 of the 12 hill stations (4 statistically significant) and increased at all 8 of the stations in the plains (2 statistically significant) (Figure 9). The increase in cool days over the plains could be partly due to the smaller difference between maximum and minimum temperatures during fog episodes, with the afternoon maximum temperature close to the minimum temperature, indicating a cold day but relatively warmer night (Manandhar, 2006). The number of warm nights, i.e. nights in which the daily minimum temperature was above the 90th percentile (TN90p), increased at all 20 stations (17 statistically significant) (Figure 10). The number of cool nights, i.e. nights in which the daily minimum temperature was below the 10th percentile (TN10p) decreased at 14 stations (7 statistically significant), and increased at 6 stations, all in the hills, (2 statistically significant).

The warm spell duration indicator (WSDI), i.e. the annual count of days with at least 6 consecutive days with a maximum temperature greater than the 95th percentile, increased on average by 15.7 days decade^{-1} (Table 3). The WSDI increased at all 12 hill/mountain stations and 2 plains stations (13 statistically significant) and decreased at the remaining 6 plains stations, but the trend was not statistically significant. The cold spell duration indicator (CSDI), i.e. the annual count of

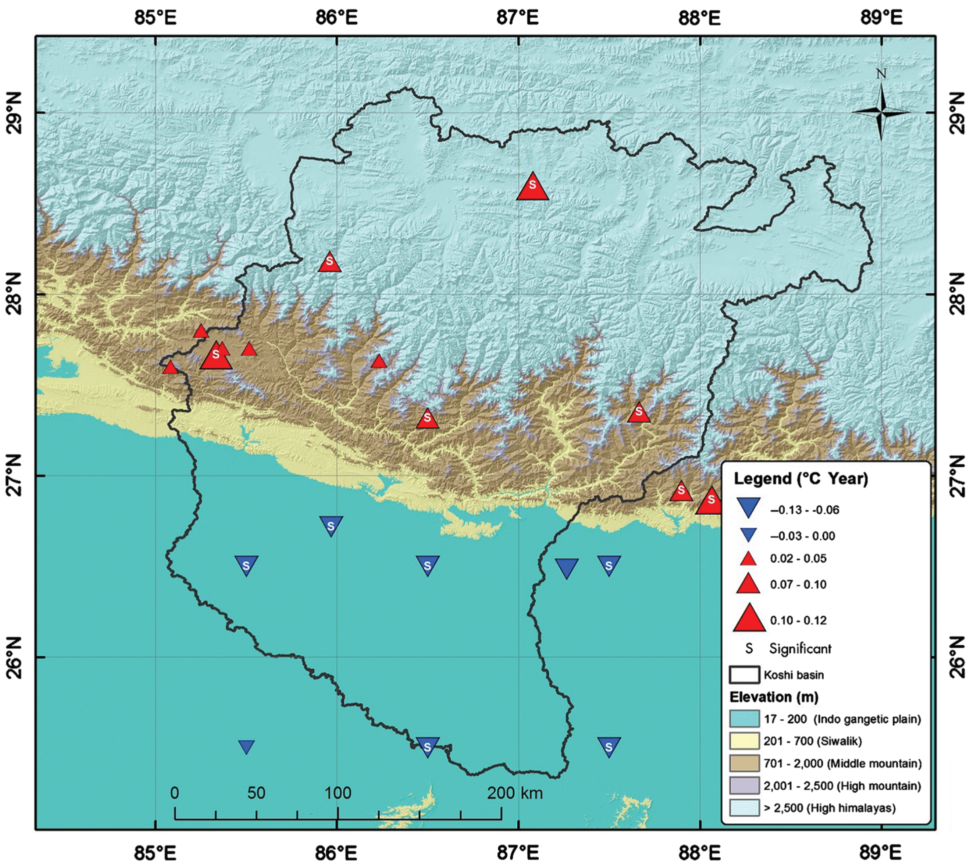

Figure 7. Trends in monthly minimum value of daily maximum temperature (TXn).

days with at least 6 consecutive days with a minimum temperature less than the 10th percentile, decreased on average by 0.4 days decade^{-1}. The CSDI decreased at five hill/mountain stations (three statistically significant) and all eight plains stations (one significant), and increased at the remaining seven hill/mountain stations (none significant) (Table 3). Taken together, the results suggest that overall days are becoming warmer.

The diurnal temperature range (DTR) remained constant on average, but this was the result of opposing trends within the basin. The DTR increased at 10 of the 12 hill/mountain stations (all statistically significant), and decreased at all of the plains stations (6 statistically significant). The decrease in DTR over the IGs is probably due to the minimum temperature warming faster than the maximum temperature. This finding is consistent with previous studies in Nepal using daily temperature data from 1971 to 2006 (Baidya *et al.*, 2008), and with previous global studies using daily global data (Alexander *et al.*, 2006) and monthly global data (Jones *et al.*, 1999), and regional studies using daily data (Yan *et al.*, 2002; Klein Tank *et al.*, 2006).

3.3. Rainfall indices

Figure 11 shows the average annual total wet day rainfall across the 50 rainfall stations in the Koshi basin from 1975 to 2010. There was considerable fluctuation, but no significant long-term trend, which is consistent with the findings of Klein Tank *et al.* (2006) and You *et al.* (2008). This study was mainly concerned with trends in precipitation extremes. Various rainfall-related indices (Table 4) were calculated for the 50 stations; the results are summarized in Table 4 and discussed in more detail below.

The monthly maximum 1-day precipitation (RX1day) decreased at 27 of the 50 stations (6 statistically significant), and increased at 23 stations (3 statistically significant), including all except one of the plains stations located at or below 100 masl (Figure 12). Similarly, the number of consecutive dry days (RR <1 mm, CDD) increased at 47 of the 50 stations (12 statistically significant). The number of consecutive wet days (RR ≥ 1 mm, CWD) increased at 33 of the 50 stations (5 statistically significant) and decreased at 17 (3 statistically significant). These findings are partially consistent with previous studies by Manton *et al.* (2001), which indicate a decrease in the monthly maximum 1-day precipitation using daily rainfall data from 1961 to 1998 in Southeast Asia; and by Singh *et al.* (2014) and Sivakumar and Stefanski (2011), which indicate an increase in the frequency of drought and increasing trend of CDD. The trend in CWD may be of more concern than the trend in CDD as it can give an idea of whether an area is experiencing more extremes in precipitation during the rainy season (Kruger, 2006), particularly important where people are living on flood-prone areas and when most agricultural activity takes place. And also CDD

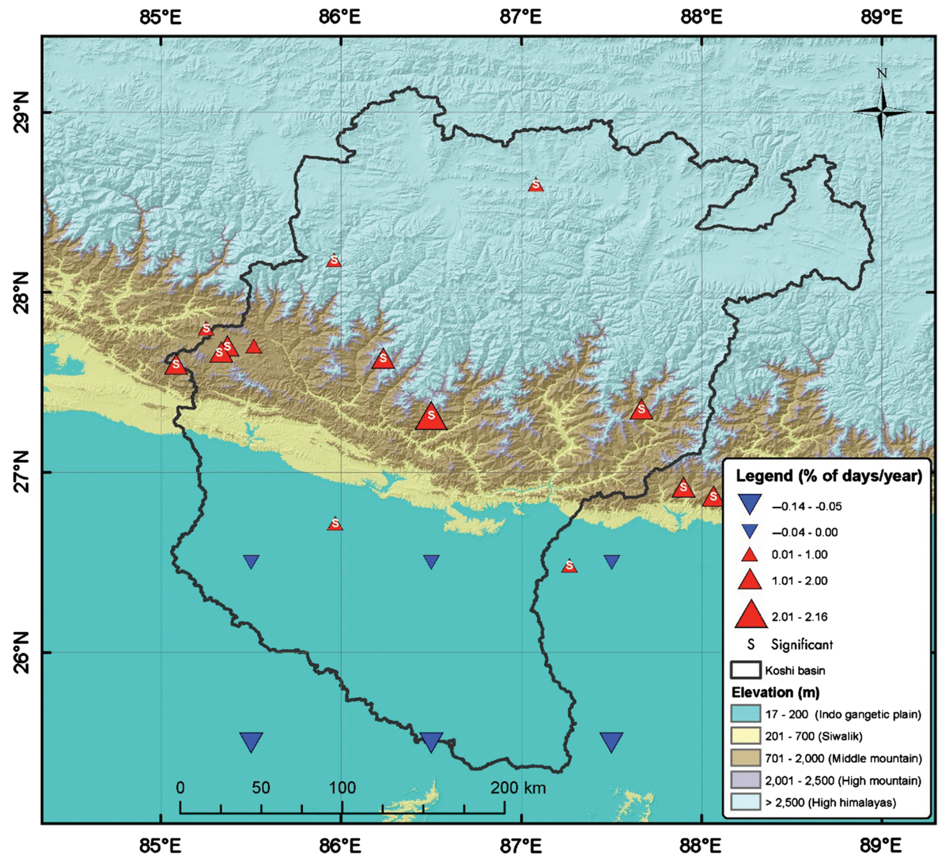

Figure 8. Trends in the percentage of days in which TX > 90th percentile (TX90p).

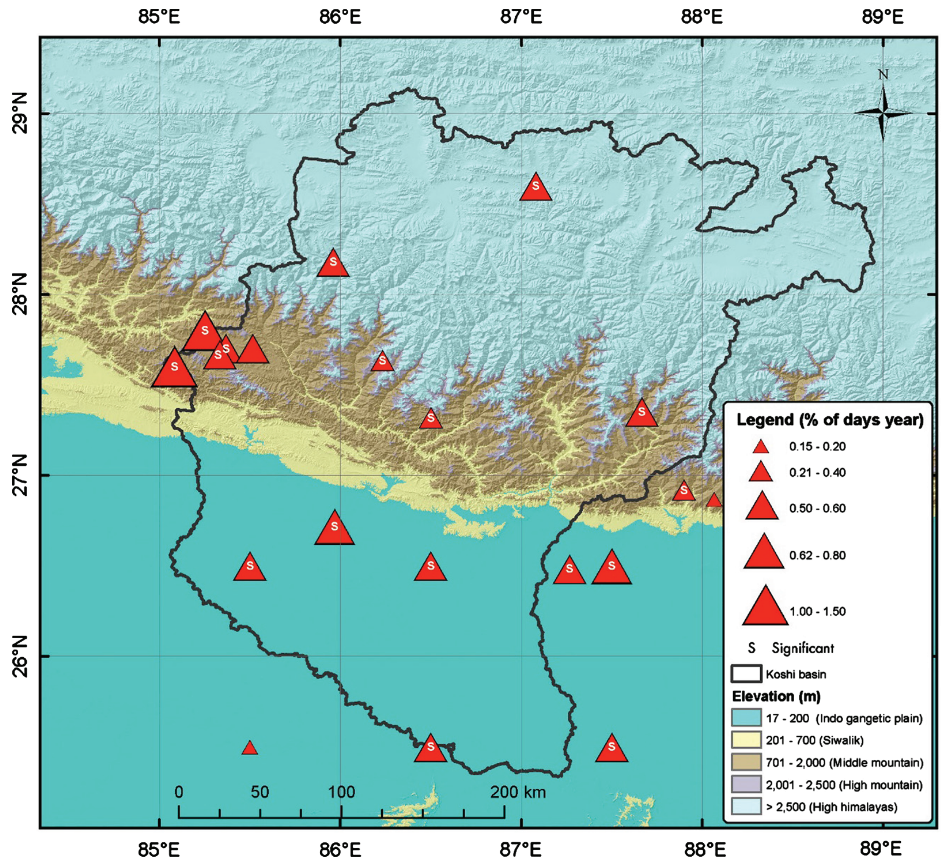

Figure 9. Trends in the percentage of days in which TX < 10th percentile (TX10p).

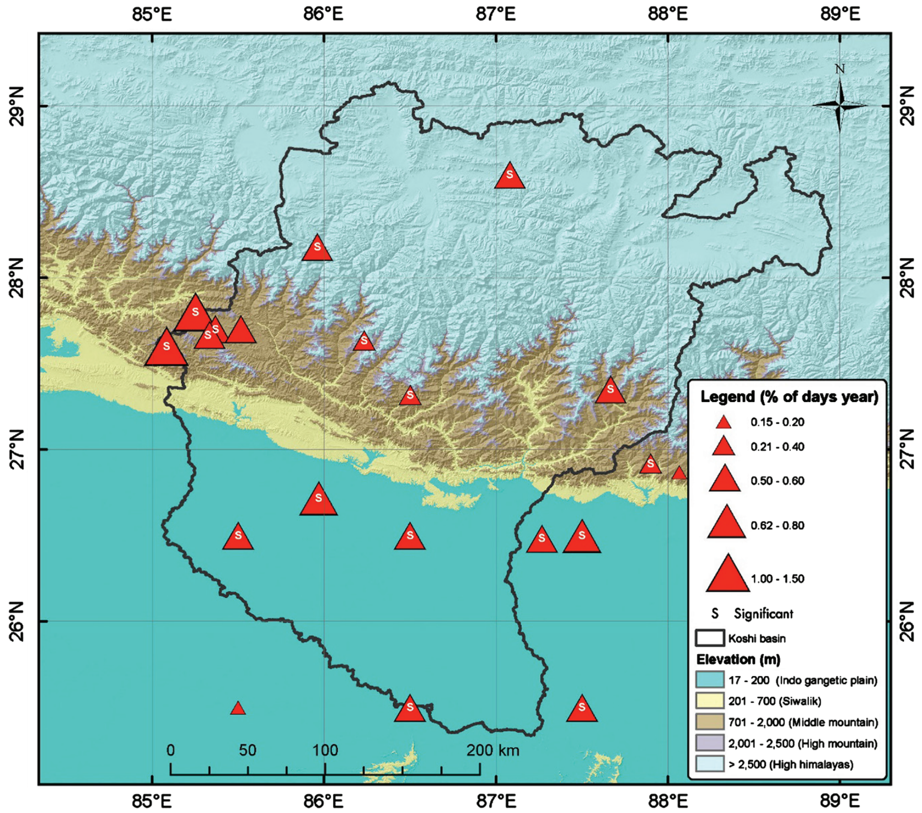

Figure 10. Trends in the percentage of days in which TN > 90th percentile (TN90p).

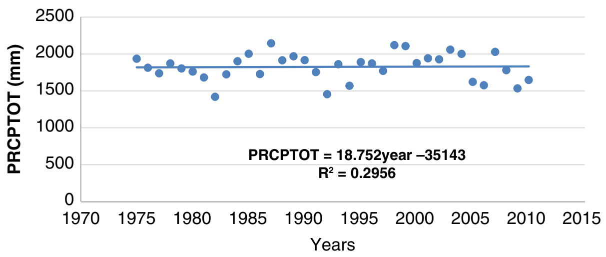

Figure 11. Average annual total wet day rainfall across the Koshi river basin.

largely reflects events during the dry season in a monsoonal climate and is therefore of limited importance.

The monthly maximum consecutive 5-day precipitation (RX5day) increased on average by 6.1 mm decade^{-1}. RX5day increased at 30 stations (2 statistically significant) and decreased at 20 stations (2 statistically significant). The annual count of heavy precipitation days with precipitation ≥ 10 mm (R10), 20 mm (R20), or 50 mm (R50), increased at 32 (3 statistically significant), 31 (3 statistically significant), and 32 (8 statistically significant) of the 50 stations (64%) respectively. This is consistent with the results reported by Singh *et al.* (2014), Baidya *et al.* (2008), and Alexander *et al.* (2006).

The annual total precipitation on very wet days (days with rainfall >95th percentile; R95p) and that on extremely wet days (R99P) increased over Koshi basin which is consistent with the results of the study by Caesar *et al.* (2011). Overall, R95P increased at 30 stations (8 statistically significant) and decreased at 20 (4 statistically significant, Figure 13); while R99P increased at 24 stations (3 statistically significant) and decreased at 26 (3 statistically significant). Some stations showed a very high increase (up to 153 mm decade^{-1} on the IGs) and others a marked decrease (up to −161 mm decade^{-1} in the mid-mountains). The results indicate an overall increase in precipitation extremes.

The annual total wet day precipitation (PRCPTOT) increased on average by 24.7 mm decade^{-1}, but there was a mixed pattern of increasing and decreasing trends across the basin. PRCPTOT increased at 30 stations (4 statistically significant) and decreased at 20 (4 statistically significant). Some stations showed a marked increase (up to 262 mm decade^{-1} in the plains) and some a marked decrease (up to −285 mm decade^{-1} in the mid-mountains) (Figure 14). These results are consistent with previous studies by Baidya *et al.* (2008).The simple daily intensity index (SDII) also increased on average at a rate of 0.3 mm day^{-1} decade^{-1}. Taken together the results indicate that overall rainfall over the Koshi basin is increasing.

The changes in precipitation extremes for 1975 to 2010 are not as significant as the temperature extremes, but do indicate heavier rainfall over fewer days in many places, with an increase in drought periods, and marked variation between the plains areas and hills and mountains, as well as local variations, especially within the hill and mountain areas. The finding that the precipitation changes are less significant than those for temperature are consistent with

Table 4. Trends in annual rainfall indices over the Koshi basin.

Stn Index	Lat. (DD)	Long. (DD)	Elev. (m)	RX1day mm	RX5day mm	SDII mm/ day	R10 mm	R20 mm	R50 mm	CDD days	CWD days	R95p (mm)	R99p (mm)	PRCP TOT (mm)
S55655 (China)	28.60	87.06	4300 (HH)	1.63	5.64	0.29	0.24	0.17	0.08	0.40	0.02	13.14	12.22	15.37
S55664 (China)	28.18	85.96	3310 (HH)	1.39	2.32	0.10	0.05	0.07	0.11	−0.19	0.81	10.11	12.16	20.64
SI1219 (Nepal)	27.50	86.58	2378 (HM)	0.15	0.45	**0.06**	0.09	0.11	0.01	0.36	0.07	4.84	0.22	3.51
SI1043 (Nepal)	27.70	85.52	2163 (HM)	0.36	1.09	−0.03	0.02	0.07	−0.02	0.85	0.09	−1.11	0.30	3.33
SI1204 (Nepal)	27.35	86.75	2143 (HM)	**−1.46**	−0.45	**−0.19**	**0.41**	−0.04	**−0.12**	0.13	**1.01**	**−9.52**	−3.12	−0.33
SI1007 (Nepal)	27.80	85.25	2064 (HM)	−0.45	−0.09	−0.06	−0.20	−0.17	−0.02	1.02	0.31	−0.63	−0.02	−5.28
SI1103 (Nepal)	27.63	86.23	2003 (HM)	**0.56**	1.19	**0.08**	0.25	0.32	0.07	0.27	0.13	**6.53**	**4.56**	**13.18**
SI1102 (Nepal)	27.67	86.05	1940 (MM)	**−0.83**	0.09	−0.03	−0.33	−0.06	0.04	0.70	−0.23	2.35	0.25	−4.94
SI1001 (Nepal)	28.28	85.38	1900 (MM)	−0.08	0.62	0.04	0.48	**0.27**	0.00	0.36	0.16	5.21	−0.90	9.26
SI1406 (Nepal)	27.20	87.93	1829 (MM)	0.37	0.38	0.04	0.27	**0.25**	0.05	0.10	0.39	2.16	1.64	7.76
SI1403 (Nepal)	27.55	87.78	1780 (MM)	0.07	0.39	**0.06**	0.13	0.14	**0.06**	0.41	0.10	**7.55**	3.17	6.42
SI1405 (Nepal)	27.35	87.67	1732 (MM)	0.75	1.23	−0.02	0.53	0.21	**0.00**	−2.65	0.08	1.04	−1.01	13.35
SI1206 (Nepal)	27.32	86.50	1720 (MM)	−0.07	0.56	0.04	0.01	0.05	0.03	0.55	0.07	2.28	−0.60	2.75
SI1416 (Nepal)	26.87	88.07	1678 (MM)	−0.29	−0.48	0.03	−0.22	−0.16	−0.05	**1.08**	−0.23	−4.55	−1.24	−13.19
SI1224 (Nepal)	27.55	86.38	1662 (MM)	**−0.91**	−0.71	0.01	0.01	−0.22	**−0.06**	0.30	−0.41	**−8.20**	−2.23	**−14.22**
SI1015 (Nepal)	27.68	85.20	1630 (MM)	0.07	−1.25	**−0.21**	**−1.06**	**−0.55**	**−0.18**	0.59	**−0.84**	**−8.49**	−1.84	**−28.51**
SI1301 (Nepal)	27.55	87.28	1497 (MM)	−1.20	−2.01	−0.02	0.19	0.28	**0.02**	−0.27	0.33	−4.40	−8.78	7.31
SI1022 (Nepal)	27.58	85.40	1400 (MM)	−0.61	−0.58	−0.01	**−0.23**	−0.10	**−0.08**	0.40	0.03	**−7.23**	−2.96	**−9.69**
SI1029 (Nepal)	27.67	85.33	1350 (MM)	−0.36	−0.64	−0.03	−0.17	−0.08	−0.03	**1.07**	−0.03	−4.07	−1.38	−3.98
SI1030 (Nepal)	27.70	85.37	1336 (MM)	0.35	0.88	0.03	−0.02	0.14	0.02	**1.02**	−0.03	2.51	0.10	2.75
SI1303 (Nepal)	27.28	87.33	1329 (MM)	−0.37	−0.78	0.01	0.22	0.12	**0.02**	0.78	0.03	−0.16	−0.39	3.93
SI1407 (Nepal)	26.92	87.90	1300 (MM)	0.11	−0.38	**0.18**	−0.19	−0.04	0.07	0.35	−0.13	5.09	0.50	−0.97
SI1027 (Nepal)	27.78	85.90	1220 (MM)	**−1.37**	**−2.33**	−0.12	0.27	0.02	−0.14	0.90	0.52	**−16.13**	**−6.09**	−6.54
SI1325 (Nepal)	27.37	87.15	1190 (MM)	−0.74	−0.83	**0.12**	0.03	0.11	**−0.02**	0.60	−0.08	−3.43	−4.02	−3.32
SI1213 (Nepal)	26.93	86.52	1175 (MM)	**−3.04**	**−4.18**	−0.04	−0.07	0.04	**−0.17**	0.91	−0.08	**−14.6**	**−5.93**	**−11.36**
SI1307 (Nepal)	26.98	87.35	1160 (MM)	−0.01	0.99	0.02	−0.05	−0.05	**0.02**	**1.06**	0.01	0.28	0.23	−2.28
SI1115 (Nepal)	27.45	85.82	1098 (MM)	−0.68	0.30	**−0.17**	−0.13	−0.06	−0.03	0.85	0.03	0.32	−0.48	−0.60
SI1038 (Nepal)	27.72	85.18	1085 (MM)	−0.20	0.03	−0.01	−0.17	−0.06	0.00	1.00	−0.12	−0.42	0.56	−3.64
SI919 (Nepal)	27.42	85.17	1030 (MM)	2.15	3.71	**0.17**	0.54	0.41	0.13	**1.25**	0.09	13.37	8.04	24.51
SI1004 (Nepal)	27.92	85.17	1003 (MM)	−0.12	−1.33	**0.13**	−0.42	−0.09	−0.05	1.14	**−0.41**	−1.04	−0.23	−11.91
SI1311 (Nepal)	26.82	87.28	444 (S)	−0.29	0.82	−0.01	−0.17	−0.24	**−0.02**	0.10	**−0.26**	−0.41	−1.37	−6.44
SI1305 (Nepal)	27.13	87.28	412 (S)	**−0.87**	−1.34	0.00	0.17	0.00	**−0.05**	**1.26**	0.07	−3.26	**−2.43**	0.56
SI1308 (Nepal)	26.93	87.33	365 (S)	0.29	1.30	0.08	0.07	0.00	**0.08**	**1.32**	0.02	5.07	2.23	4.16
SI1320 (Nepal)	26.70	87.27	200 (IG)	−0.74	−0.44	0.09	0.09	0.18	0.07	**1.38**	−0.12	1.96	−1.02	6.20
SI1316 (Nepal)	26.82	87.17	183 (IG)	−1.13	1.23	0.03	0.18	0.11	0.03	0.65	**0.15**	3.00	−1.62	4.25
SI1112 (Nepal)	26.92	86.17	165 (IG)	−0.84	1.48	**0.23**	**−0.35**	−0.09	0.05	**1.63**	0.05	4.22	−2.05	−1.48
SI1312 (Nepal)	26.62	87.38	152 (IG)	−1.12	1.14	−0.04	−0.12	0.09	0.09	1.01	0.03	1.04	−4.46	3.44
SI909 (Nepal)	27.17	84.98	130 (IG)	−1.23	−1.51	0.03	−0.08	0.07	0.05	0.39	**0.13**	−1.06	−3.34	0.55
SI1409 (Nepal)	26.63	87.98	122 (IG)	1.00	1.56	0.10	0.01	0.09	**0.26**	0.85	−0.13	**13.87**	1.63	**18.22**
SI911 (Nepal)	27.07	84.97	115 (IG)	−0.69	−0.06	0.05	0.06	0.07	0.07	**1.37**	**0.20**	0.70	−2.10	3.59
SI1216 (Nepal)	26.65	86.22	102 (IG)	0.63	0.41	−0.13	0.02	−0.08	−0.02	**1.27**	**0.20**	0.33	0.60	0.03
SI1223 (Nepal)	26.55	86.75	91 (IG)	0.89	2.94	0.01	0.09	0.04	**0.02**	1.10	−0.03	3.84	1.89	3.59
SI1111 (Nepal)	26.72	85.97	90 (IG)	**2.38**	4.80	**0.24**	0.09	0.13	0.11	**1.30**	0.03	**10.34**	4.81	12.25
X875Y265 (India)	26.50	87.50	79 (IG)	1.17	3.00	0.10	0.26	0.35	0.18	0.22	0.02	6.23	3.48	20.32
X865Y265 (India)	26.50	86.50	77 (IG)	0.39	1.77	−0.01	−0.37	−0.29	0.01	0.79	−0.06	2.44	0.58	−7.46
SI1319 (Nepal)	26.48	87.27	72 (IG)	0.10	0.89	0.01	0.01	0.07	**0.02**	1.16	−0.02	0.85	0.44	3.11
X855Y265 (India)	26.50	85.50	63 (IG)	1.11	−1.97	−0.14	0.28	−0.01	−0.10	0.05	0.09	−5.61	0.35	1.68
X855Y255 (India)	25.50	85.50	50 (IG)	−0.95	−1.01	0.01	0.01	0.09	0.04	0.26	0.02	−2.26	−2.48	−1.66
X865Y255 (India)	25.50	86.50	39 (IG)	2.33	**6.10**	**0.20**	**0.59**	**0.51**	0.15	0.91	0.12	**15.29**	**10.26**	**26.15**
X875Y255 (India)	25.50	87.50	33 (IG)	**3.46**	**5.53**	0.11	**0.48**	0.16	0.15	1.03	0.13	**14.05**	**9.35**	**19.06**
Average				0.02	0.61	0.03	0.04	0.05	0.02	0.67	0.05	1.27	0.35	2.47
Stations with + trend				23	30	31	32	31	32	47	33	30	24	30
Stations with − trend				27	20	18	18	19	18	3	17	20	26	20
Stations With 0 trend				0	0	1	0	0	0	0	0	0	0	0
%With + trend stations				46	60	62	64	62	64	94	66	60	48	60
%With-trend stations				54	40	36	36	38	36	6	34	40	52	40
%With no trend stations				0	0	2	0	0	0	0	0	0	0	0

Bold indicates statistically significant at 5%.

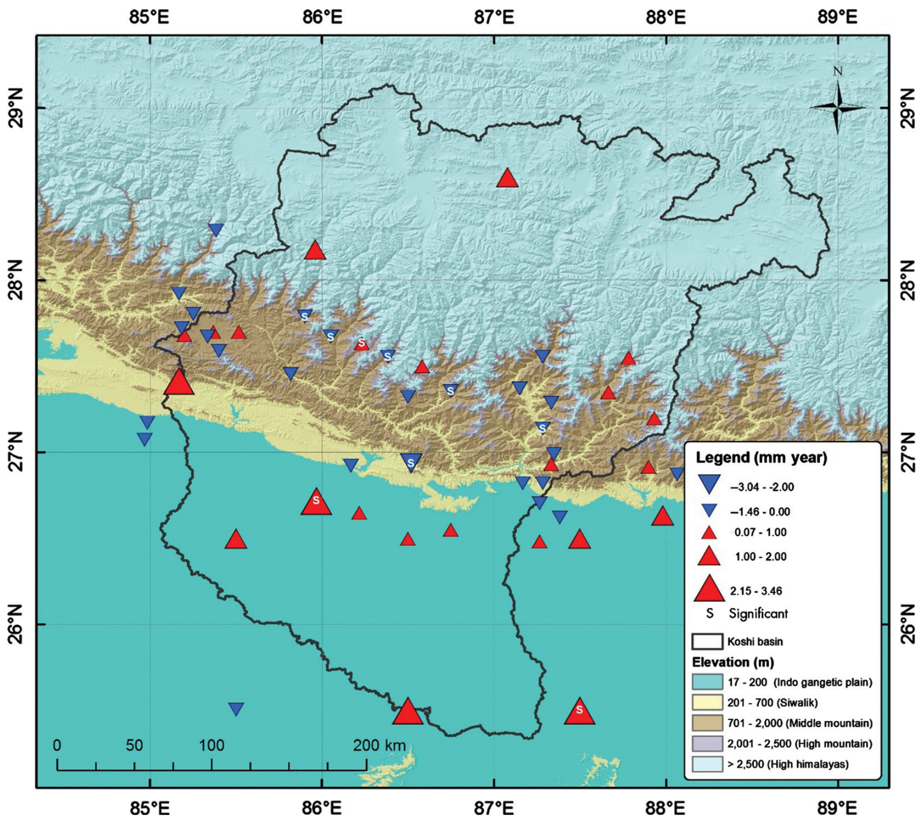

Figure 12. Trends in monthly maximum 1-day precipitation (Rx1day).

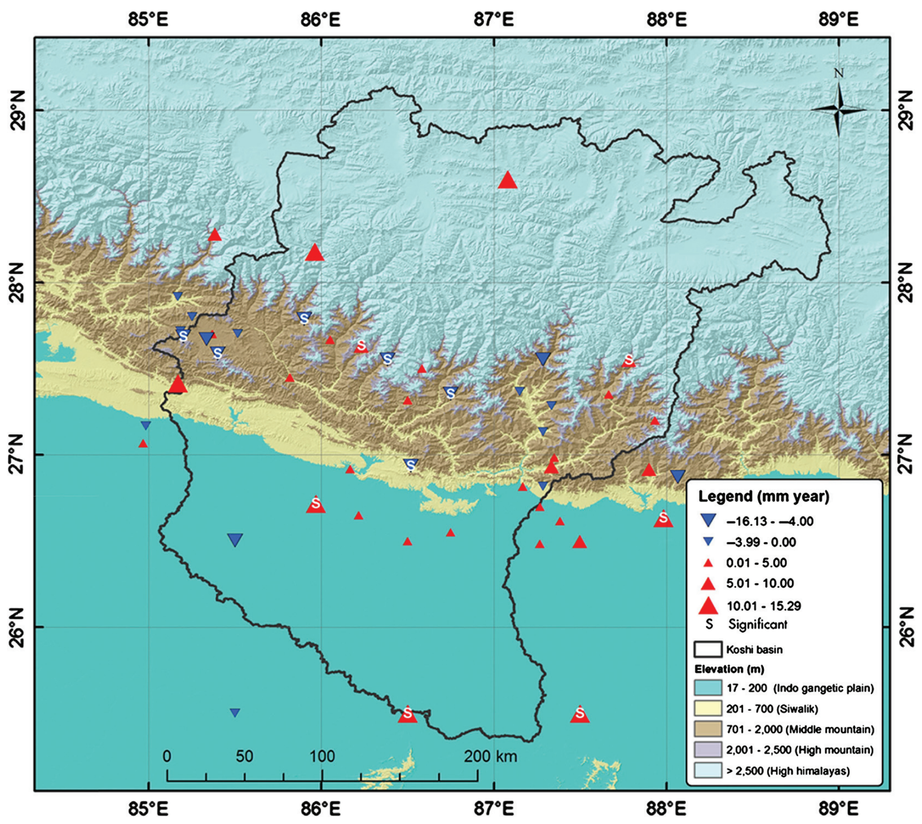

Figure 13. Trends in annual total PRCP when RR > 95th percentile (R95p).

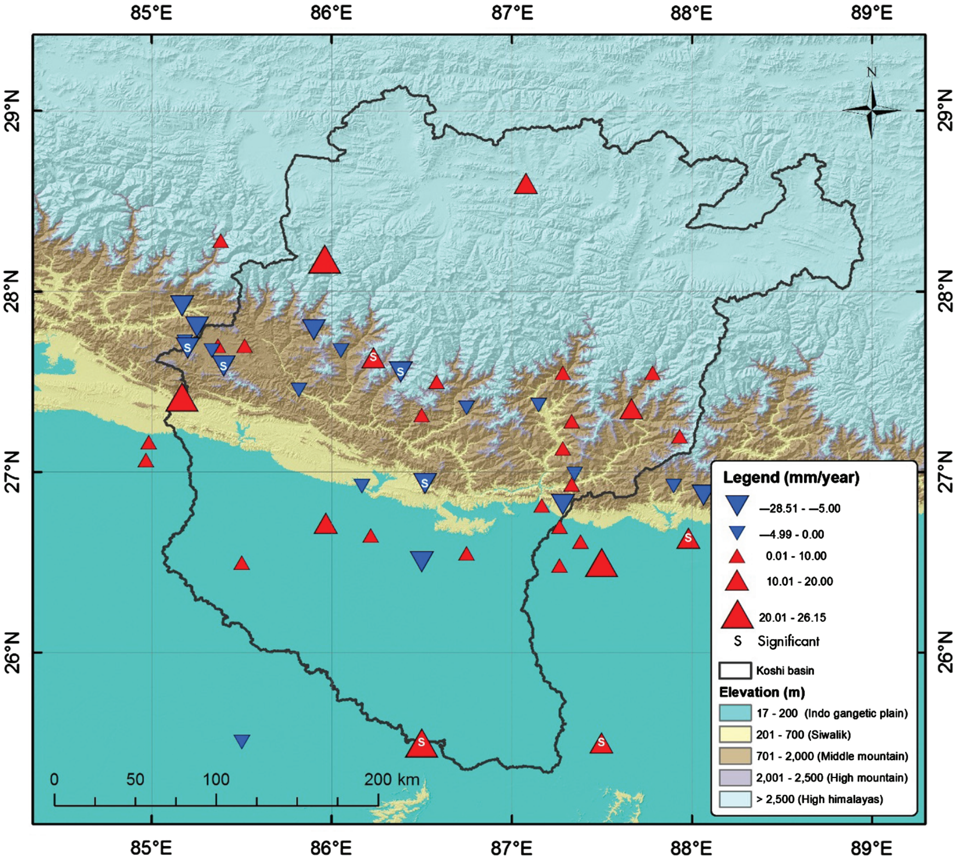

Figure 14. Trends in annual total precipitation in wet days with RR ≥ 1 mm (PRCPTOT).

the results of the study by King *et al.* (2013); Klein Tank *et al.* (2006) and others have found this result too.

4. Conclusion

The study looked at the long-term trends and patterns in temperature and precipitation extremes and average values over the Koshi basin from 1975 to 2010. There was a clear indication of a warming trend in maximum and minimum seasonal temperatures, but with some spatial variation. While the stations in the hills and mountains generally showed a significant warming, in the plains warming was absent or temperatures (especially maximum temperature) were decreasing. Warming was apparent in all seasons, but with the least change in the post-monsoon season. The most significant increment in minimum temperature was seen in winter.

The results also showed widespread changes in temperature extremes associated with warming, especially for those indices derived from daily minimum temperature; most of these results were statistically significant. More than 90% of stations showed an increase in monthly minimum value of minimum temperature, and 70% of stations a decrease in the annual occurrence of nights in which the daily minimum temperature was below the 10th percentile. In general, there were large coherent patterns in the basin with contrasting trends between the hills and mountains and the plains. The rising trends in maximum and minimum values of daily maximum and minimum temperatures clearly show that temperatures in the basin are increasing, although the statistical significance was not sufficient for a definitive analysis. In general, a much larger percentage of stations showed significant changes in minimum temperature than in maximum temperature, and the minimum temperature increased three times faster than the maximum temperature. All stations in the basin showed an increase in the number of warm nights (TN90p), most statistically significant, and 70% a decrease in the number of cool nights (TN10p). On average the number of cool days (TX10p) is decreasing and the number of warm days (TX90p) is increasing. The duration of warm spells is increasing (WSDI) at a rate of 15.7 days decade^{-1} while the duration of cold spells (CSDI) is slightly decreasing.

The changes in the plains region were often different to those in the hills and mountains. The number of summer days, monthly maximum and minimum values of daily maximum temperature (TXx, TXn), percentage of days when the maximum value was >90th percentile (TX90p), percentage of days when the minimum value was <10th percentile (TN10p), warm and cold spell duration (WSDI and CSDI), and DTR all decreased at the stations in the IGs, while the number of cold days increased. This difference may in part be due to the increased duration of fog episodes in the plains in recent years. Overall the results of the study are consistent with those of previous studies, but provide special insights into the differences between the mountains and the plains.

Overall, the number of heavy precipitation days (R10) and number of extremely heavy precipitation days (R20) show increasing trend at 62 and 64% of weather stations, respectively and the number of very wet days increased at a faster rate than the number of extremely wet days. The SDII also increased slightly. The precipitation results indicated a tendency towards shorter and more intense spells of rainfall. Consecutive dry days (CDD) increased at a high rate (6.7 days decade^{-1}) at most stations, and much higher than the number of consecutive wet days (CWD) (0.5 days decade^{-1}). Overall, the annual total precipitation increased over the basin between the start and end of the period, as did the annual total wet day precipitation, but there was no consistent trend. Taken together, the results suggest that there is a mixed pattern of changes in precipitation extremes which support the idea that the Koshi basin is becoming generally wetter, but the changes were not statistically significant at all stations.

The changes in DTR, duration of warm and cold spells, total precipitation, SDII, and consecutive dry days, could have significant societal impacts. The Koshi basin is home to a large population; many live below the poverty line and their coping capacity, especially in marginal areas, is low. Thus, there is a strong need to understand the vulnerability of the basin's inhabitants and to mainstream good practices for adaptation. This study will help the relevant stakeholders to look more clearly at the frequency, magnitude, and duration of climate extremes in the water resources sector, and the potential socioeconomic impact, especially the impact on agriculture, health, and other climate-related livelihood activities.

Acknowledgements

This study was undertaken under the Himalayan Climate Change Adaptation Programme (HICAP). HICAP is implemented jointly by ICIMOD, CICERO, and GRID-Arendal in collaboration with local partners and is supported by the Governments of Norway and Sweden. The authors would like to express their sincere gratitude to the Department of Hydrology and Meteorology (DHM), Nepal, for providing the data and Mr. Gauri Shankar Dangol of ICIMOD for preparing the maps. The views and interpretations in this publication are those of the authors. They are not necessarily attributable to ICIMOD and do not imply the expression of any opinion by ICIMOD concerning the delimitation of frontiers or boundaries.

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