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Analyses of Observed and Anticipated Changes in Extreme Climate Events in the Northwest Himalaya

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Abstract: In this study, past (1970-2005) as well as future long term (2011-2099) trends in various extreme events of temperature and precipitation have been investigated over selected hydro-meteorological stations in the Sutlej river basin. The ensembles of two Coupled Model Intercomparison Project (CMIP3) models: third generation Canadian Coupled Global Climate Model and Hadley Centre Coupled Model have been used for simulation of future daily time series of temperature (maximum and minimum) and precipitation under A2 emission scenario. Large scale atmospheric variables of both models and National Centre for Environmental Prediction/National Centre for Atmospheric Research reanalysis data sets have been downscaled using statistical downscaling technique at individual stations. A total number of 25 extreme indices of temperature (14) and precipitation (11) as specified by the Expert Team of the World Meteorological Organization and Climate Variability and Predictability are derived for the past and future periods. Trends in extreme indices are detected over time using the modified Mann-Kendall test method. The stations which have shown either decrease or no change in hot extreme events (*i.e.*, maximum T_{Max}, warm days, warm nights, maximum T_{Min}, tropical nights, summer days and warm spell duration indicators) for 1970–2005 and increase in cold extreme events (cool days, cool nights, frost days and cold spell duration indicators) are predicted to increase and decrease respectively in the future. In addition, an increase in frequency and intensity of extreme precipitation events is also predicted.

Keywords: extreme events; warm days; warm nights; tropical nights; summer days

1. Introduction

An extreme weather or climate event is an event that is rare at a particular place and time of year [1]. According to Easterling *et al.*[2], extreme events can be grouped into two broad categories: (1) yearly extreme events or weather events based on simple statistics such as very low or very high daily temperature and heavy daily rainfall, and (2) more complex event-driven extremes, e.g., droughts, floods, heat waves and hurricanes which do not necessarily occur every year at a given location. These extreme events are of great concern because slight changes in frequency or intensity of extreme events can have important effects on society and natural ecosystems. An increase in frequency of heat waves may increase number of fatalities and decreased personal productivity while an increase in frequency and intensity of the extreme events of precipitation may increase flash flooding problems. The world as a whole witnessed huge losses of life, extensive damage to crops and properties due to these events in the past [2–4].

The augmented vulnerabilities of human society and natural ecosystems to such events have called for the study of extreme weather events [5,6]. In Europe, Klein Tank and Können[7] investigated daily records of more than 100 meteorological stations and computed trends in daily temperature and precipitation indices for the period of 1946–1999. Their results indicated a rise in indices of wet extremes and annual number of warm extremes followed by a decrease in annual number of cold extremes. Moberg and Jones [8] studied patterns of changes in extreme indices over Central and Western Europe for the 20th century. They derived six indices of precipitation extreme and four indices of temperature extremes from the daily observed records (1901–1999), collected from 81 meteorological stations. The five out of six extreme indices of precipitation showed rising trends during the winter season over most parts of Europe. Similar kinds of studies were also undertaken by many authorsin Europe [9–11]. The study of Plummer *et al.* [12] performed in Australia, showed increases as well as decreases in extreme temperature and precipitation indices. In South America, no consistent changes in indices of daily temperature (maximum) were observed; however, there were increases in the number of warm nights [13].Vincent and Mekis [14] analyzed a long time series (1900–2003) of daily homogenized temperature and adjusted precipitation data for all of Canada in North America. They observed decreases in the frequency of cold nights, cold days and frost days with increases in warm nights, warm days and summer days. The analysis of precipitation indices revealed increases in the amount of daily precipitation; however, decreases in daily intensity and dry spell length were detected.The studies conducted by Manton *et al.* [15] over Southeast Asia and the South Pacific, and by Sheikh *et al.*[4] over South Asia revealed increasing trends in the annual number of warm days and warm nights coupled with decreasing trends in the annual number of cold days and cold nights.

India, a tropical country in South Asia is highly vulnerable to extreme events. In the recent past, the country has witnessed a significant rise in frequency and intensity of extreme events of temperature and precipitation, causing immeasurable damage of properties and loss of life. The occurrence of an unprecedented heat wave in 2003 (May–June) was responsible for the death of 1600 in Andhra Pradesh [3]. A record of 944 mm of rainfall within 24 hours in Mumbai (Maharashtra) caused economic losses of $3.5 billion including 429 lives [4]. Furthermore, in June 2013, massive flooding was observed in the Indian states of Himanchal Pradesh, Uttarakhand, Haryana, Delhi and Uttar Pradesh, but the vulnerability was highest in Uttarakhand. Flooding in Uttarakhand triggered by a continuous torrential downpour from 14 to 17 June 2013 led to India's worst natural disaster since the 2004 tsunami. As of 16 July 2013, according to figures provided by the Uttarakhand government, more than 5700 people were "presumed dead". Furthermore, economic losses of around $16,199,580 billion was estimated and more than 2232 houses were destroyed, causing displacement of millions of people in the state [16].

A number of studies on different spatial scales have been carried out over India for studying trends and variability in extreme indices of temperature [3,17,18] and precipitation [19–21]. However, the research work carried out on temperature and precipitation related extremes over the Himalayan region are very limited [22]. In addition, in most of the studies, trends in extreme events have been examined only for historical periods. However, the Intergovernmental Panel on Climate Change (IPCC) in its Fourth Assessment Report (AR4) has shown concerns for extreme weather events as some types of weather extremes are anticipated to become more persistent in the future [1]. The mighty Himalaya along with the El Nino/Southern Oscillation (ENSO) affects atmospheric circulation and exhibits significant control over the meteorological and hydrological conditions of the Indian subcontinent [23,24]. A minor shift in mean state of climate over the Himalaya has the potential to have catastrophic consequences on the socio-economic survival of millions of people inhabiting the Indo-Gangetic plains. Furthermore, the regionalization of results in climatologically varied regions like the Himalaya may not give correct patterns of extreme events. This has encouraged research leading to detailed analysis of extreme events in different isolated locations of the Himalaya. Therefore, more area-specific studies over the Himalayan region are required for designing mitigation and adaptation measures to deal with these changes.

In view of these concerns, the present study has been carried out to study past (1970–2005) and future (2011–2099) trends in extreme events of temperature and precipitation over selected stations located in the Sutlej river basin (Himachal Pradesh), Northwest Himalaya (NWH). For this purpose, a total number of 25 extreme indices of temperature (14) and precipitation (11) as specified by the Expert Team of the World Meteorological Organization (WMO) Commission for Climatology (CCL)/Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) are derived from daily data of temperature (maximum and minimum) and precipitation at individual stations using RClimdex. Trends in extreme indices are detected over time using the modified Mann–Kendall test method. Further, behavior of extreme indices observed in the past are studied and compared with future periods in order to see changes.

2. Study Area

Himachal Pradeshsituated in NWH is a hilly state of India. It is bounded in the North and Northwest by Jammu and Kashmir, in the East by Tibet (China), in the Southeast by Uttarakhand, in the South by Haryana and Uttar Pradesh and in the Southwest by Punjab. Sutlej, a Trans Himalayan river flows through the state. It originates from the Mansarovar–Rakastal lakes near the Dharma Pass (Western Tibet) at an altitude of 4570m and enters Himanchal Pradesh through Shipki La. In Himachal Pradesh, it flows at about 320km and cuts a gorge in Naina Dhar before entering the Punjab plains. The high straight gravity dam of Bhakra of 225.55m has been constructed here. The basin formed by Sutlej river in Himanchal Pradesh can be divided into five sub-basins as shown in Table 1. The area selected for this study is the middle catchment of Sutlej river basin which extends from Rampur to Kasol. Geographically, the basin is locked up between latitudes 31°05′00″N to 31°39′26″N latitudes, and longitudes 76°51′11″E to 77°45′17″E (Figure 1).

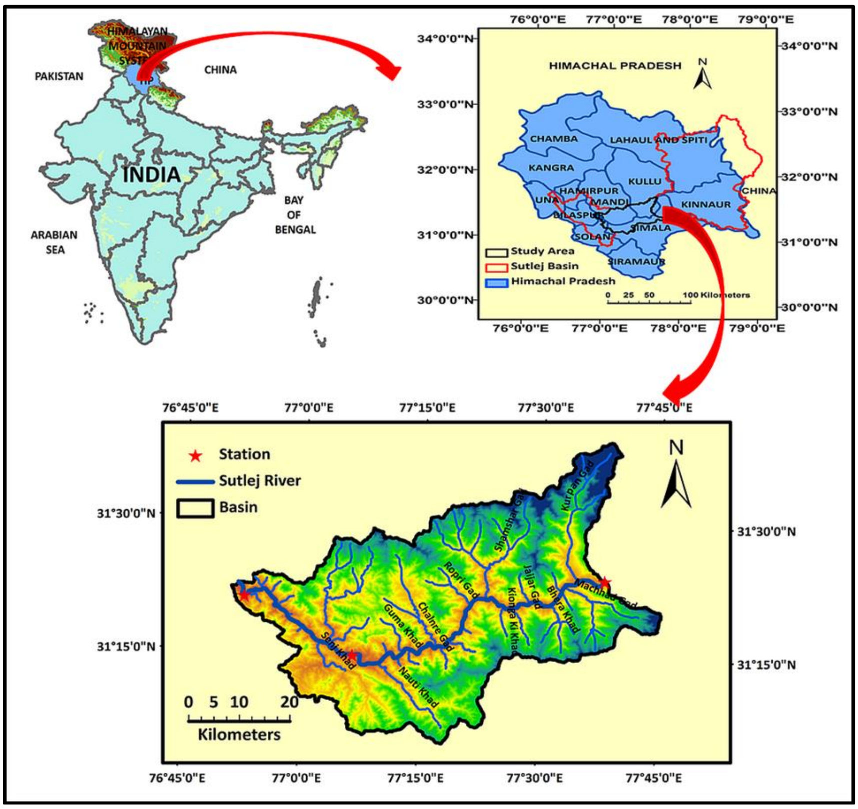

Figure 1. Location map of study area.

The large disparities in the topographical relief have resulted in a variety of climates causing different types of flora and fauna in the Sutlej basin. Besides terrestrial flora and fauna, the Sutlej basin is very rich in aquatic life. The entire Sutlej river up to the Govind Sagar reservoir and the tributaries of the river are home to 51 fish species belonging to 13 taxonomic families. The vegetation types in this region vary from Tropical to Alpine.

Table 1. The salient topographical and hydro-meteorological features of Sutlej catchment up to Bhakara dam.

Reach	Catchment Area (km^2)	Elevation Range (m)	Average Annual Rainfall (mm)	Major Source of Contributions to the Stream Flow
Spiti Valley	7084	3300–5300	Scarce (<50)	Snow and glacier
Namgia to Rampur	6490	3000–4800	Little (<150)	Snow and rainfall
Rampur to Sunni	2068	1200–3000	1000–1500	Rainfall
Sunni to Kasol	700	900–2000	910–1630	Rainfall
Kasol to Bhakhra	3108	600–2000	1520	Rainfall

3. Data

The daily time series of temperature (maximum and minimum) and precipitation data is prerequisite for the analysis of extreme weather events. The observed records of periods 1970–2005 were procured from Bhakara Beas Management Board (BBMB), India. Only the stations having at least 360 days of data in a year (*i.e.*, for >98% days in a year) are included in the analysis. The raw data generally inherit inhomogeneities or discontinuities in the time series [15]. The presence of erroneous outliers in time series may also impact the indices calculation and their trends [25]. To remove these anomalies in the data, the daily time series of each station has been first scrutinized visually to identify any obvious outliers, trends and potential discontinuities. Then, the procedure discussed by Kothawale *et al.* [3] has been adopted for screening of outliers from the time series. The inhomogeneities in the records are then tested using RHtestsV4 software [26]. If no major inhomogeneities were detected for a station, then it has been allowed for analysis; otherwise, it is rejected. Based on the quality control and homogeneity test, data for a set of three stations, namely, Kasol (662m), Sunni (655m), and Rampur (976m) have been prepared for further analysis. The location of these four stations is marked in Figure 1, as shown above. The future (2011–2099) daily time series of temperature and precipitation data under A2 scenario for these stations have been generated from third Generation Canadian Coupled Global Climate Model (CGCM3) and Hadley Centre Coupled Model, version 3 (HadCM3). A2 scenarios are considered as the worst among all the available scenarios and are characterized by high concentrations of CO2 (850 ppm) gas. There is a probability of the highest rise in temperature compared with other scenarios [1]. The large scale atmospheric variables (predictors) for nearest grid in the study area are obtained from the websites of Data Access Integration (DAI) and Canadian Climate Impacts Scenarios (CCIS), respectively.

The predictors simulated by CGCM3 model and HadCM3 model are available on grid resolution of 3.75° latitude × 3.75° longitude and 2.5° latitude × 3.75° longitude, respectively. The study area is registered within grid box 21X_16Y (latitude 31.54°N × 75.00°E longitude) and box_22X_16Y (latitude 31.54°N × 78.75°E longitude) of CGCM3 model. Furthermore, it is registered within grid box 21X_22Y (latitude 32.5°N × 75.00°E longitude), box_22X_23Y (latitude 30°N × 78.75°E longitude) and box 22X_22Y (latitude 32.5°N × 78.75° E longitude) of the HadCM3 model. The predictors of both models have been downscaled using statistical downscaling techniques at individual stations, and bias corrected future (2011–2099) time series of temperature and precipitation are generated for all the stations. The steps involved in downscaling of predictors for these stations and methods adopted for bias correction of downscaled time series have been described in detail by Singh *et al.* [27].

4. Methodology

A total number of 27 extreme indices defined by WMO CCL/CLIVAR ETCCDMI are based on thresholds and percentiles [19,26]. Of this set, 16 indices are related with temperature and 11 to precipitation. These are shown in Tables 2 and 3 for temperature and precipitation,respectively. The aim of the ETCCDMI is to determine a standardized set of indices allowing for uniformity in comparison across different regions. The derivation of these extreme indices has been discussed by Zhang and Yang [28].

In the present study, only 14 extreme indices of temperature, excluding ice days (ID0) and growing season length (GSL), and 11 indices of precipitation have been examined as these are found to be relevant to the study area. The indices are calculated on yearly time scales at 10% level of statistical significance using RClimDex developed by Zhang and Yang [28]. The methodology adopted in computation of extreme indices for temperature and precipitation has been shown in Figure 2 with the help of flow chart. The daily time series of maximum temperature, minimum temperature and precipitation are input in RClimdex, and a Quality Check function is run to check inhomogeneities present in the data. Then, extreme indices of temperature and precipitation are derived using Calculation of Extreme Indices function. The trends in extreme indices are detected using modified Mann–Kendall (MK) test method [29]. It is a non-parametric test method. In modified MK test, test statistics Z_s is used to check monotonic trends in time series, whereas magnitude of change is determined from Sen's slope estimator (Q) [30].

Table 2. List of expert team on climate change detection, monitoring and indices (ETCCDMI) extreme temperature indices.

ID	Indicator Name	Definitions	Units
CSDI	Cold spell duration indicators	Annual count of days with at least 6 consecutive days when TN < 10th percentile	Days
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C
FD0	Frost days	Annual count when TN(daily minimum) <0 °C	Days
ID0	Ice days	Annual count when TX(daily maximum) <0 °C	Days
GSL	Growing season Length	Annual count between first span of at least 6 days with TG >5 °C after winter and first span after summer of 6 days with TG <5 °C	Days
SU25	Summer days	Annual count when TX(daily maximum) >25°C	Days
TR20	Tropical nights	Annual count when TN(daily minimum) >20°C	Days
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	Days
TX10p	Cool days	Percentage of days when TX < 10th percentile	Days
TN90p	Warm nights	Percentage of days when TN > 90th percentile	Days
TX90p	Warm days	Percentage of days when TX > 90th percentile	Days
WSDI	Warm spell duration indicators	Annual count of days with at least 6 consecutive days when TX > 90th percentile	Days

TX daily maximum temperature, TN daily minimum temperature, TG daily mean temperature.

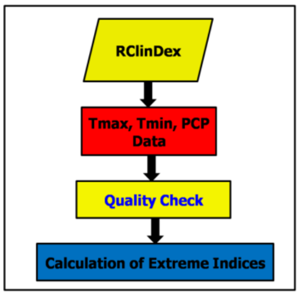

Figure 2. Methodology adopted in computation of extreme indices.

Table 3. List of ETCCDMI extreme precipitation indices.

ID	Indicator Name	Definitions	Units
CDD	Consecutive dry days	Maximum number of consecutive days with RR <1mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR ⩾1mm	Days
PRCPTOT	Annual total wet-day precipitation	Annual total PCP in wet days (RR ⩾1mm)	mm
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
R10	Number of heavy precipitation days	Annual count of days when PCP ⩾10mm	Days
R20	Number of very heavy precipitation days	Annual count of days when PCP ⩾20mm	Days
Rnn	Number of days above nn mm	Annual count of days when PCP ⩾nn mm, nn is user defined threshold	Days
R95p	Very wet days	Annual total PCP when RR > 95th percentile	mm
R99p	Extremely wet days	Annual total PCP when RR > 99th percentile	mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP ⩾1.0mm) in the year	mm /day

PCP = Precipitation, RR = rainfall rate.

5. Results and Discussions

5.1. Annual Trends in Extreme Indices of Temperature for 1970–2005

The results showing trends in annual extreme indices of temperature for the past (1970–2005) have been presented in Table 4. Large variations in trends of annual indices of temperature are perceived as it varies spatially, *i.e.*, station-wise. On the other hand, statistically significant decreasing trends innumber of tropical nights (TR20), warm nights (TN90p), magnitude of monthly minimum value of daily maximum temperature (TXn) and minimum temperature (TNn) including maximum T_{Min} (statistically insignificant) are detected. However, no particular trends could be perceived in number of summer days (SU25), cool nights (TN10p), warm days (Tx90p) and warm spell duration indicators (WSDI) and in magnitude of maximum T_{Max}. Only five indices have shown statistically significant trends at Sunni. Out of these five, three (cool nights, diurnal temperature range (DTR) and maximum T_{Max}) have revealed upward trends while the others (tropical nights and warm nights) showed downward trends. In addition, statistically insignificant rising trends in number of frost days (FD0), cold spell duration indicators, and in amount of minimum T_{Max} are detected. The other indices of temperature, *i.e.*, summer days, maximum T_{Min}, minimum T_{Min}, warm days and warm spell duration indicator exhibited no trends for the above periods. The annual trend analysis of extreme temperature indices performed over Rampur station indicates rise (statistically significant) in DTR and minimum T_{Max}. No specific changes in frequency and intensity of frost days, summer days, maximum T_{Min}, warm nights and duration of warm spells are identified during this period. The indices (cool nights and spell of cold duration) which have shown upward trends over Kasol and Sunni revealed statistically insignificant downward trends at Rampur.

In general, annual trends observed in these extreme indices are not in line with previous studies conducted by taking India as a whole. Panda *et al.* [17] examined trends in extreme indices of temperature over India using high resolution ($1^\circ \times 1^\circ$) daily gridded data. Their studies indicate rises in hot extreme events (TXx, TX90p, TN90p, TNx, TR20, SU25 and WSDI) and decreases in cold extreme events (TX10p, TN10p, TXn, FD and CSDI) over most parts of the country for the period of 1970–2005. However, no such patterns in hot and cold extreme indices are observed for the study area as a whole. The observed trend pattern can be best explained by taking isolated stations because these are located at different altitudes with different climatic conditions as well as physiographic and environmental conditions.

Table 4. Annual trends in extreme temperature indices at different stations.

Indicator Name	Kasol		Sunni		Rampur	
	Z_s	Q (°C or day/year)	Z_s	Q (°C or day/year)	Z_s	Q (°C or day/year)
Cold spell duration indicator	(+)	0.06	(+)	0.18	(−)	0.24
Diurnal temperature range	(+)	0.01	(+) *	0.05	(+) *	0.04
Frost days	NA	NA	(+)	0.55	NT	-
Summer days	NT	-	NT	-	NT	-
Tropical nights	(−) *	−0.67	(−) *	−0.66	(+)	0.19
Max T_{Max}	NT	-	(+) *	0.11	(+)	0.04
Max T_{Min}	(−)	−0.03	NT	-	NT	-
Min T_{Max}	(−) *	-0.06	(+)	0.06	(+) *	0.07
Min T_{Min}	(−) *	-0.03	NT	-	(+)	0.02
Cool nights	NT	-	(+) *	0.20	(−)	−0.11
Cool days	(+) *	0.13	(−)	−0.07	(−)	−0.08
Warm nights	(−) *	−0.18	(−) *	−0.32	NT	-
Warm days	NT	-	NT	-	(+)	0.2
Warm spell duration indicators	NT	-	NT	-	NT	-

* indicates results are statistically significant at 10% level, NT stands for No Trend.

5.2. Annual Trends in Extreme Indices of Precipitation for 1970–2005

The results showing trends in annual extreme indices of precipitation for the period of 1970–2005 are presented in Table 5. Statistically insignificant rises in amount of maximum one day precipitation (RX1day), consecutive dry days (CDD) and very wet days (R95p) is observed at Kasol. In addition, fall in maximum five day precipitation amount (RX5day), number of heavy precipitation day >10 mm (R10), number of heavy precipitation day >20 mm (R20), number of days above 5 mm (Rnn), consecutive wet days (CWD) and annual total wet day precipitation (PCPTOT) have been detected. However, results are statistically significant only for consecutive wet days at given level of significance (10%). The remaining two indices, *viz.*, simple daily intensity index (SDII) and extremely wet days (R99p) exhibit no trends for the period of 1970–2005 at Kasol.

Trends computed for extreme precipitation indices at Sunni have shown rising as well as decreasing trends. Seven out of 11 indices have negative trends. However, most of the time, trends are statistically insignificant. These are consecutive wet days (statistically significant), number of days above 5 mm (statistically significant), maximum one day precipitation amount, maximum five day precipitation amount, number of heavy precipitation day >10 mm, number of heavy precipitation day >20 mm and annual total wet day precipitation. The statistically insignificant rise in consecutive dry days, simple daily intensity index and very wet days has been reported for the period of 1970–2005; however, no particular trend is detected for extremely wet days. The patterns observed in extreme indices of precipitation here are somewhat similar to Kasol where decreasing trend in consecutive wet days, number of days above 5 mm, maximum five day precipitation amount, number of heavy precipitation day >10 mm, number of heavy precipitation day >20 mm and increasing trend in consecutive dry days have also been detected. The study of annual trend analysis performed at Rampur differs in patterns from other two stations where eight out of eleven indices have shown increasing trend. Statistically significant increasing trends in amount of maximum one day precipitation, maximum five day precipitation amount, very wet days, extremely wet days and simple daily intensity index have been observed for the period of 1970–2005. Besides, statistically insignificant increasing trends in consecutive dry days, number of heavy precipitation day >20 mm and annual total wet day precipitation are reported, followed by decreasing trend in number of days above 5 mm and number of heavy precipitation day >10 mm.

Table 5. Annual trends in extreme precipitation indices at different stations.

Indicator Name	**Kasol**		**Sunni**		**Rampur**	
	Z_s	**Q (mm or day/year)**	**Z_s**	**Q (mm or day/year)**	**Z_s**	**Q (mm or day/year)**
Consecutive dry days	(+)	0.26	(+)	0.15	(+)	0.33
Consecutive wet days	(−) *	0.11	(−) *	0.07	NT	-
Annual total wet-day precipitation	(−)	2.35	(−)	3.80	(+)	1.54
Max 1-day precipitation amount	(+)	0.55	(−)	0.23	(+)*	0.85
Max 5-day precipitation amount	(−)	0.72	(−)	0.81	(+)*	0.87
Number of heavy precipitation days >10 mm	(−)	0.15	(−)	0.15	(−)	0.09
Number of very heavy precipitation days >20 mm	(−)	0.10	(−)	0.03	(+)	0.08
Number of days above nn mm (nn =5)	(−)	0.19	(−) *	0.33	(−)	0.14
Very wet days	(+)	1.20	(+)	0.99	(+) *	3.70
Extremely wet days	NT	-	NT	-	(+) *	1.78
Simple daily intensity index	NT	-	(+)	0.02	(+) *	0.05

* indicates results are statistically significant at 10% level, NT stands for No Trend.

5.3. Annual Trends in Extreme Indices of Temperature for 2011–2099

The results showing future (2011–2099) annual trends in extreme temperature indices under A2 scenario of CGCM3 model are presented in Table 6. Nine out of fourteen indices have revealed positive trends at Kasol. Statistically significant increasing trends in summer days, tropical nights, maximum T_{Min}, minimum T_{Max}, maximum T_{Min}, warm nights and warm days are predicted at Kasol for the future periods. The three indices, *viz.*, cold spell duration, cool nights and cool days have shown negative trends; however, trends are statistically significant only for cool nights and cool days. More or less similar patterns in trends of projected extreme temperature indices are observed at Sunni where nine (six statistically significant) indices have positive trends and five have negative (three statistically significant) trends. The increasing trends are predicted for summer days, tropical nights, maximum T_{Max}, maximum T_{Min}, minimum T_{Max}, minimum T_{Min}, warm nights, warm days and warm spell duration indicator. Conversely, negative trends are predicted for indices such as cold spell duration indicators, diurnal temperature range, cool nights, cool days and number of frost days. However, trends are statistically significant only for diurnal temperature range, cool nights and cool days. The study predicts rise in five indices *viz.*, summer days, tropical nights, maximum T_{Max}, warm days and warm spell duration indicator out of fourteen at Rampur. Cold spell duration indicator, diurnal temperature range and cool nights show negative trends; however, no trend is predicted for the remaining six indices.

Similarly, annual trends predicted in extreme temperature indices under the A2 scenario of HadCM3 model are given in Table 7. Statistically significant increasing trends in summer days, tropical nights, maximum T_{Min}, minimum T_{Max}, and warm nights are predicted for all three stations. The decrease in number of cool nights is expected as all of the stations showed statistically significant downward trends for the future periods.

Table 6. Annual trends in extreme temperature indices at different stations under A2 scenario of the third generation Canadian coupled global climate (CGCM3) model.

Indices	Kasol		Sunni		Rampur	
	Z_s	Q (°C or day/year)	Z_s	Q (°C or day/year)	Z_s	Q (°C or day/year)
Cold spell duration indicator	(−)	0.18	(−)	0.3	(−)	0.18
Diurnal temperature range	NT	-	(−) *	0.03	(−) *	0.02
Frost days	NA	-	(−)	0.14	NT	-
Summer days	(+) *	0.41	(+) *	0. 21	(+) *	0.11
Tropical nights	(+) *	0.30	(+) *	0. 66	(+) *	0. 41
Max T_{Max}	(+) *	0.03	(+) *	0.02	(+)	0.01
Max T_{Min}	(+) *	0.02	(+) *	0. 05	NT	-
Min T_{Max}	(+) *	0. 04	(+) *	0.02	NT	-
Min T_{Min}	(+) *	0.02	(+) *	0. 04	NT	-
Cool nights	(−) *	0.12	(−) *	0.21	(−) *	0.12
Cool days	(−) *	0.08	(−) *	0.03	NT	-
Warm nights	(+) *	0.13	(+) *	0.25	(+) *	0. 13
Warm days	(+) *	0.11	(+) *	0.04	NT	-
Warm spell duration indicator	(+)	0.02	(+)	0.07	(+)	0.02

* indicates results are statistically significant at 10% level, NT stands for No Trend.

Table 7. Annual trends in extreme temperature indices at different stations under the A2 scenario of the Hadley Centre coupled model, version 3 (HadCM3) model.

Indices	Kasol		Sunni		Rampur	
	Z_s	Q (°C or day/year)	Z_s	Q (°C or day/year)	Z_s	Q (°C or day/year)
Cold spell duration indicator	(−)	0.14	(−)	0.39	(−)	0.39
Diurnal temperature range	(−) *	0.01	NT	-	(−) *	0.03
Frost days	NA	-	(−)	0.09	NT	-
Summer days	(+) *	0.22	(+) *	0.60	(+) *	0.29
Tropical nights	(+) *	0.34	(+) *	0.67	(+) *	0.84
Max T_{Max}	NT	-	(+) *	0.08	(+) *	0.05
Max T_{Min}	(+) *	0.03	(+) *	0.06	(+) *	0.03
Min T_{Max}	(+) *	0.02	(+) *	0.04	(+) *	0.02
Min T_{Min}	(+) *	0.01	NT	-	(+)*	0.02
Cool nights	(−) *	0.01	(−) *	0.23	(−) *	0.23
Cool days	NT	-	(−) *	0.14	(−) *	0.08
Warm nights	(+) *	0.10	(+) *	0.24	(+) *	0.24
Warm days	NT	-	(+) *	0.12	(+) *	0.07
Warm spell duration indicator	(+)	0.04	(+)	0.31	(+)	0.10

* indicates results are statistically significant at 10% level, NT stands for No Trend.

5.4. Annual Trends in Extreme Indices of Precipitation for 2011–2099

The results derived from annual trend analysis of extreme precipitation indices under A2 scenario of CGCM3 model and HadCM3 model are presented in Tables 8 and 9 respectively. Large variability in patterns of extreme precipitation indices at Sunni and Rampur have been predicted under both of the models. The study predicts increase in frequency and intensity of extreme indices of precipitation (consecutive wet days, annual total wet-day precipitation, maximum one day precipitation amount, maximum five day precipitation amount, number of heavy precipitation days >10 mm, number of very heavy precipitation days >20 mm, number of days above 5 mm, very wet days, extremely wet days and simple daily intensity index) in the future as all three of the stations have shown increasing trends for indices of precipitation (excluding consecutive dry days) under A2 scenario of CGCM3 model. Most of the time, these are statistically significant in nature. However, significant spatially variability in magnitudes of these extreme indices is predicted between stations as these are installed at varying height and under different climatic conditions.

Table 8. Annual trends in extreme precipitation indices at different stations under A2 scenario of CGCM3 model.

Indices	Kasol		Sunni		Rampur	
	Z_s	Q (mm or day/year)	Z_s	Q (mm or day/year)	Z_s	Q (mm or day/year)
Consecutive dry days	(−)	0.09	(−)	0.04	NT	-
Consecutive wet days	(+) *	0.10	(+) *	0.08	(+) *	0.05
Annual total wet-day precipitation	(+) *	17.39	(+) *	10.00	(+) *	5.72
Max 1-day precipitation amount	(+) *	0.98	(+) *	0.44	(+)	0.08
Max 5-day precipitation amount	(+) *	1.94	(+) *	1.11	(+) *	0.39
Number of heavy precipitation days >10 mm	(+) *	0.31	(+) *	0.28	(+) *	0.24
Number of very heavy precipitation days >20 mm	(+) *	0.25	(+) *	0.16	(+) *	0.08
Number of days above nn mm (nn =5)	(+) *	0.36	(+) *	0.38	(+) *	0.31
Very wet days	(+) *	8.49	(+) *	4.83	(+) *	1.39
Extremely wet days	(+)	4.35	(+)	1.30	(+)	0.55
Simple daily intensity index	(+) *	0.09	(+) *	0.03	(+) *	0.01

* indicates results are statistically significant at 10% level, NT stands for No Trend.

The trends predicted in extreme precipitation indices under scenarios of the CGCM3 model are in accordance with the previous study conducted over the Himalayan region. The future projections of precipitation extremes over the region using PRECIS has been carried out by Revadekar *et al.* [31]. The study projects increases in extreme precipitation events over a large area in the Himalayan region (with the exception of Jammu and Kashmir) with heavy maximum daily rainfall in the monsoon season.

Table 9. Annual trends in extreme precipitation indices at different stations under A2 scenario of HadCM3 model.

Indices	Kasol		Sunni		Rampur	
	Z_s	Q (mm or day/year)	Z_s	Q (mm or day/year)	Z_s	Q (mm or day/year)
Consecutive dry days	(+) *	0.30	(+) *	0.12	(+) *	0.04
Consecutive wet days	(+) *	0.20	NT	-	NT	-
Annual total wet-day precipitation	(+) *	14.64	(+)	0.77	(+)	0.66
Max 1-day precipitation amount	(+) *	0.65	(+)	0.25	(+)	0.03
Max 5-day precipitation amount	(+) *	1.92	(+)	0.33	(+)	0.16
Number of heavy precipitation days >10 mm	(+) *	0.22	(−)	0.01	(+)	0.03
Number of very heavy precipitation days >20 mm	(+) *	0.23	NT	-	NT	-
Number of days above nn mm (nn =5)	(+) *	0.16	(−)	0.06	(+)	0.02
Very wet days	(+) *	6.90	(+)	1.09	(+)	0.06
Extremely wet days	(+)	3.30	(+)	1.12	(+)	0.41
Simple daily intensity index	(+) *	1.11	(+) *	0.02	(+) *	0.01

* indicates results are statistically significant at 10% level, NT stands for No Trend.

6. Conclusions

The computation of fourteen temperature and eleven precipitation extreme indices for past (1970–2005) as well as future (2011–2099) periods have been carried out over three mountainous stations located in the Sutlej river basin. Furthermore, trends in these extreme indices have been investigated using the modified Mann–Kendall test method. In general, all three of the stations, namely, Kasol, Sunni and Rampur, have shown either a decrease or no change in hot extreme events (*i.e.*, maximum T_{Max}, warm days, warm nights, maximum T_{Min}, tropical nights, summer days and warm spell duration indicators) for historical periods. In addition, rises in cold extreme events (cool days, cool nights, minimum T_{Max}, frost day and cold spell duration indicators) have been observed at Sunni, excluding the number of cool days. The rest of the stations have shown mixed patterns in the trends of extreme cold events. In addition, the basin as a whole has experienced an increase in DTR. This is thought to be linked with decreases observed in maximum T_{Min} as well as in warm nights (TN90p) and increases in maximum T_{Max} (TXx).

The rising as well as decreasing trends in extreme precipitation indices have been noticed for the past periods and, most of the time, these are statistically insignificant in nature. In addition, spatial variations have also been observed in trends of extreme precipitation indices. More or less similar patterns in trends of extreme indices are found at Kasol and Sunni, and this significantly differs from Rampur. There are rises in frequency and intensity of extreme precipitation indices at Rampur as statistically significant rising trends have been observed in maximum one day precipitation, maximum five day precipitation, simple daily intensity index, very wet days and extremely wet days. Conversely, a fall in frequency of wet days has been reported at Kasol and Sunni as statistically significant decreasing trend in consecutive wet days is observed for the above periods. The discrepancies observed, in patterns of extreme events of temperature and precipitation among three stations during 1970–2005 may be attributed to the dissimilarity in physiographic characteristics and local climatic conditions of these three stations.

The patterns in extreme temperature and precipitation indices are also examined for the future periods (2011–2099) under A2 scenario of CGCM3 model and HadCM3 model. In general, increases in extreme hot events and decrease in cold extreme events is predicted at all the stations in both the models. Furthermore, statistically significant trends are detected in maximum T_{Max}, warm days, warm nights, maximum T_{Min}, tropical nights, summer days and warm spell duration indicators, cool days, cool nights and diurnal temperature range. For the future periods, rising trends in extreme precipitation indices are predicted for all the stations under A2 scenario of CGCM3 model. However, in the case of the HadCM3 model, variability in patterns of extreme indices is predicted between the stations. The future patterns in extreme temperature and precipitation indices predicted here are based on a plausible scenario (A2). This scenario represents an expected range of temperature and precipitation change in future. The large uncertainties are coupled with the quantitative estimates because the projected temperature and precipitation inherited uncertainties due to uncertainties associated with CGCM3 and HadCM3 models, and limitations of the downscaling technique in downscaling of temperature and precipitation.

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