Assessment of spatial variations in temperature and precipitation extremes in west-flowing river basin of Kutch, Saurashtra and Marwar, India

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Climate extreme event indicates the manifestation of higher or lower values (with respect to a threshold value) by a climatic variable. The goal of this study is to analyse the spatial variation in 27 indices of temperature and precipitation extremes in the west-flowing river basin of Kutch, Saurashtra and Marwar (WFR-KSM basin). Climate extreme indices were calculated using RClimDex software on 50 years of daily precipitation gridded data and 36 years of daily maximum and minimum temperature data. Theil–Sen slope was calculated as the estimator of trend in 16 extreme indices of temperature and 11 extreme indices of precipitation throughout the basin. The results indicate increase towards wetter climate extremes and a shift towards hotter climate extremes.

Keywords: Climate, precipitation, river basin, spatial variations, temperature.

NOWADAYS extreme events are witnessed with more intensity and frequency globally. Along with the established warming of climate, some types of extreme weather events have become more frequent and severe in the recent decades. Although natural changes are continuously occurring in the earth's climate system at various timescales, the current accelerated pace of changing climate, especially after the beginning of the industrial era, is attributed to anthropogenic activities. The ongoing pace of climatic variations and extremes is putting huge pressure on socio-economy along with challenging the basic subsistence requirements, mainly freshwater availability and agricultural activities.

Climate extreme events indicate the manifestation of higher or lower end values (with respect to a threshold value) by a climatic variable. Extremes form an integrated part of the stable climate, but their ongoing frequency and impact indicate anthropogenic forcing. The impacts of changing climate in the form of intense rainfall, sparse rainfall, floods and droughts are of concern. Several studies have shown that the average warming of the earth was 0.74°C over the last century and that the most of the warming occurred in last three decades[1–3]. The Intergovernmental Panel on Climate Change (IPCC) in its AR5 Synthesis Report has concluded that the climate system warming since 1950s is unequivocal and the effects of anthropogenic greenhouse gases (carbon dioxide, methane and nitrous oxide) combined with other anthropogenic drivers are its leading cause[4]. The World Meteorological Organization (WMO) Statement on the status of the global climate claims the year 2015 as the warmest one on record[5]. WMO[5] suggests that globally the number and frequency of hot days and warmer nights have increased, cold days/frost days have declined, heavy precipitation events have increased and the Asian region exhibited an increase in frequency and intensity of droughts. According to the IPCC 2007 report[1], another aspect of the projected changes is that 'wet extremes are projected to become more severe in many areas where mean precipitation is expected to increase, and dry extremes are projected to become more severe in areas where mean precipitation is projected to decrease. In the Asian monsoon region and other tropical areas there will be more flooding'.

The change in climatic variables differs spatially. To assess the variations at regional level[6], the temperature and precipitation extreme indices were calculated grid-wise. The calculated indices, known as 'ETCCDI' indices, have been selected from a core set of descriptive indices of extremes defined by the joint Expert Team on Climate Change Detection and Indices (ETCCDI; CLIVAR)[7]. RClimdex was used for the calculation of these indices with Theil–Sen (TS) slope as the indicator of trend.

Although extremes form an integral part of the stable climate, the frequency with which these occur calls for the formulation of strong mitigation and adaptation strategies. Here, we study the changes in some indices of temperature and precipitation extremes. The trend analysis will be helpful in emphasizing the anthropogenic

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impacts on changing climate and analysing them spatially will help in channellizing the mitigation and adaptation strategies at areas which require attention.

Study area

The study was carried out in the west-flowing river basin of Kutch, Saurashtra and Marwar (WFR-KSM basin), which is situated in the western part of India (Figure 1)[8–10]. The basin has the catchment of rivers flowing towards the Arabian Sea covering the states of Rajasthan (21.8%), Gujarat (63.2%) and the Union Territory of Diu (100%). It has an area of 184,865.96 sq. km with diversified relief and topographical variations. The western part of the basin has salty marsh regions of the Rann of Kutch; River Banas and the Aravalli hill ranges form the eastern boundary; River Luni spanning through desert regions of Rajasthan forms the northern region and the southern areas are covered by small seasonal rivers.

Goals and objectives

The research was carried out with a goal to spatially analyse temperature and precipitation extremes in the WFR-KSM basin. The methodology involves: (1) calculations of indices of temperature and precipitation extremes with their trends and (2) spatial interpretation of associated trends.

Software and data used

The software used were RClimDex, R script, Arc Map, MS excel and geospatial modelling environment (GME). The datasets used for the calculation of climate extreme indices were Indian Meteorological Department (IMD) daily precipitation grid (0.25° × 0.25°) from 1964 to 2013 representing 50 years of daily data, and daily maximum and daily minimum temperature data in the form of IMD temperature grid (1° × 1°) for the period 1969–2004 representing 36 years of daily data. The administrative and hydrological boundaries were used from India-WRIS (Water Resources Information System of India) web GIS.

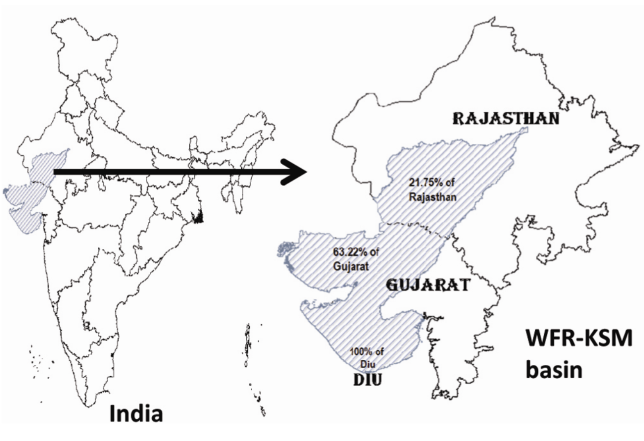

Figure 1. Location of west flowing river basin of Kutch, Saurashtra and Marwar (WFR-KSM).

Analytical methods used

The climate extreme analysis was performed for every grid by calculating 27 climate extreme indices (suggested by the ETCCDI team)[11] with their TS slope. The user friendly R-based software RClimDex was used for analysis (http://cccma.seos.uvic.ca/ETCCDI).

To gain uniform perspective on the climate extremes, the ETCCDI defined a core set of descriptive indices based on characteristics like frequency, amplitude and persistence. Frich *et al.*[12] defined a group of indices which subsequently became 'ETCCDI' indices, and the same were based on the European Climate Assessment (ECA) indices by Klein Tank *et al.*[13] for analysis of trends in the second half of the 20th century. The assessment of climate extremes using the same method is well documented globally[14–21].

Table 1 shows the indices computed, including 11 indices of precipitation extremes and 16 indices of temperature extremes.

The TS trend test was used to determine the magnitude of trend over time. The TS trend test has no assumption regarding normal distribution of residuals and their homoscedastic (having equal variance over time) nature. The TS slope estimates the changes in median value of the variable with time. In this test, simple slopes are calculated for each pair of data, and the median slope value is extracted as TS slope. Let $y_1, y_2, \ldots, y_n$ represent ordered measured observations. For each successive observation for every j which is greater than i, the pairwise slope was calculated as

$$m_{ij} = \frac{(y_j - y_i)}{j - i}.$$

The calculated pairwise slopes were ordered from smallest to largest and relabelled as $m(1)$, $m(2)$ … $m(n)$. The median slope (Q) or TS slope can be computed depending on whether the sample has even or odd observations as

$$Q = \begin{cases} m_{([N+1]/2)} & \text{if } N = \text{odd}, \\ \dfrac{(m_{([N/2])} + m_{([N+2])/2})}{2} & \text{if } N = \text{even}. \end{cases}$$

Methodology

The methodology was divided into three steps. The first step was the generation of software compatible data from the raw data. India Meteorological Department (IMD) daily

Table 1. Indices of daily precipitation and temperature extremes

Index	Description
Daily precipitation extremes	
Max 1-day precipitation (RX1day)	Maximum amount of precipitation in 1 day
Max 5-day precipitation (Rx5day)	Maximum amount of precipitation in 5 days
Simple daily intensity index (SDII)	Average of amount of precipitation on wet days
Heavy precipitation days (R10)	Number of (count) days when daily precipitation ≥ 10 mm
Very heavy precipitation days (R20)	Number of (count) days when daily precipitation ≥ 20 mm
Number of days above 64.5 mm (R_64pt5)	Count of days when precipitation ≥ 64.5 mm
Consecutive dry days (CDD)	Maximum length of dry spell (daily rainfall < 1 mm)
Consecutive wet days (CWD)	Maximum length of wet spell (daily rainfall ≥ 1 mm)
Very wet days (R95p)	Precipitation when rainfall >95th percentile (very wet)
Extremely wet days (R99p)	Precipitation when rainfall >99th percentile (extremely wet)
Annual total wet-day precipitation (PRCPTOT)	Total precipitation in wet days when rainfall ≥ 1 mm
Daily temperature extremes	
Frost days (FD0)	Count of days when daily minimum temperature < 0°C
Ice days (ID0)	Count of days when daily maximum temperature < 0°C
Summer days (SU25)	Count of days when daily maximum temperature > 25°C
Tropical nights (TR20)	Count of days when daily minimum > 20°C
Max T_{max} (TXx)	Monthly maximum value of daily maximum temperature
Max T_{min} (TNx)	Monthly maximum value of daily minimum temperature
Min T_{max} (TXn)	Monthly minimum value of daily maximum temperature
Min T_{min} (TNn)	Monthly minimum value of daily minimum temperature
Cool nights (TN10p)	Count of days when minimum temperature < 10th percentile
Cool days (TX10p)	Count of days when maximum temperature < 10th percentile
Warm nights (TN90p)	Count of days when minimum temperature > 90th percentile
Warm days (TX90p)	Count of days when maximum temperature > 90th percentile
Warm spell duration indicator (WSDI)	Count of days with at least six consecutive days when TX > 90th percentile
Cold spell duration indicator (CSDI)	Count of days with at least six consecutive days when TN < 10th percentile
Diurnal temperature range (DTR)	Mean difference between maximum and minimum temperature
Summer days (SU45)	Count when daily maximum temperature > 45°C

gridded data with a spatial resolution of 0.25° × 0.25° for rainfall and 1° × 1° for temperature were extracted and daily data of rainfall, maximum and minimum temperature were processed to ASCII file in a specific format as required by RCLimDex as input data file.

The second step was the calculation of climate extreme indices and trends using RClimDex. The data were loaded in RClimDex and quality check (QC) was performed. The QC results were thoroughly checked and then 'indices calculation' was performed. The resulting indices series were calculated and stored in a sub-directory called indices.

The third and final step involved the generation of information maps for climate extreme indices spatially. The calculated indices for all grids were brought to a single table using MS-Excel and ASAP utilities (which is MS-Excel add-on tool) in a format that can be attached to climate grid shapefile. The final trends with error and *P* value were attached to the grids using geoprocessing and information maps were generated in ArcMap. The GME software was used for averaging the indices from grids to the basin.

Results

The climate extremes were interpreted separately as extreme indices of precipitation (Figure 2) and extreme indices of temperature (Figure 3) throughout the basin. There were 348 grids for precipitation (0.25° × 0.25°) and 32 grids for maximum and minimum temperature (1° × 1°).

Trend in extreme indices of temperature

Frost days and ice days are not a feature of the climate of this area. However, two grids represent the presence of slope in frost days in the northeastern border of the basin with slope ranging from –0.2 and –0.1 days/decade. Not a single day can be classified as ice day in the region. In summer, all grids indicated increasing trend, except one with slope ranging from –0.1 to 3.8 days/decade. The grids located in Rajasthan constituting desert area showed greater increase compared to those located in the plains of Gujarat, Kathiawar and Kutch peninsula. For tropical nights, spatial variation existed in the grids which were a part of the coastal and hilly border of the basin, while adjacent ones showed increasing trend. The central grids exhibited a declining trend for tropical nights and overall majority of the grids (20 grids, i.e. 62.5%) showed a rise for tropical nights with time, while 12 grids showed a negative trend. The slope ranged from –2.2 to 4.2 days/decade.

Max T_{max} showed overall an increasing trend with time. The rise in Max T_{max} ranged from 0.1° to 0.3°C/decade.

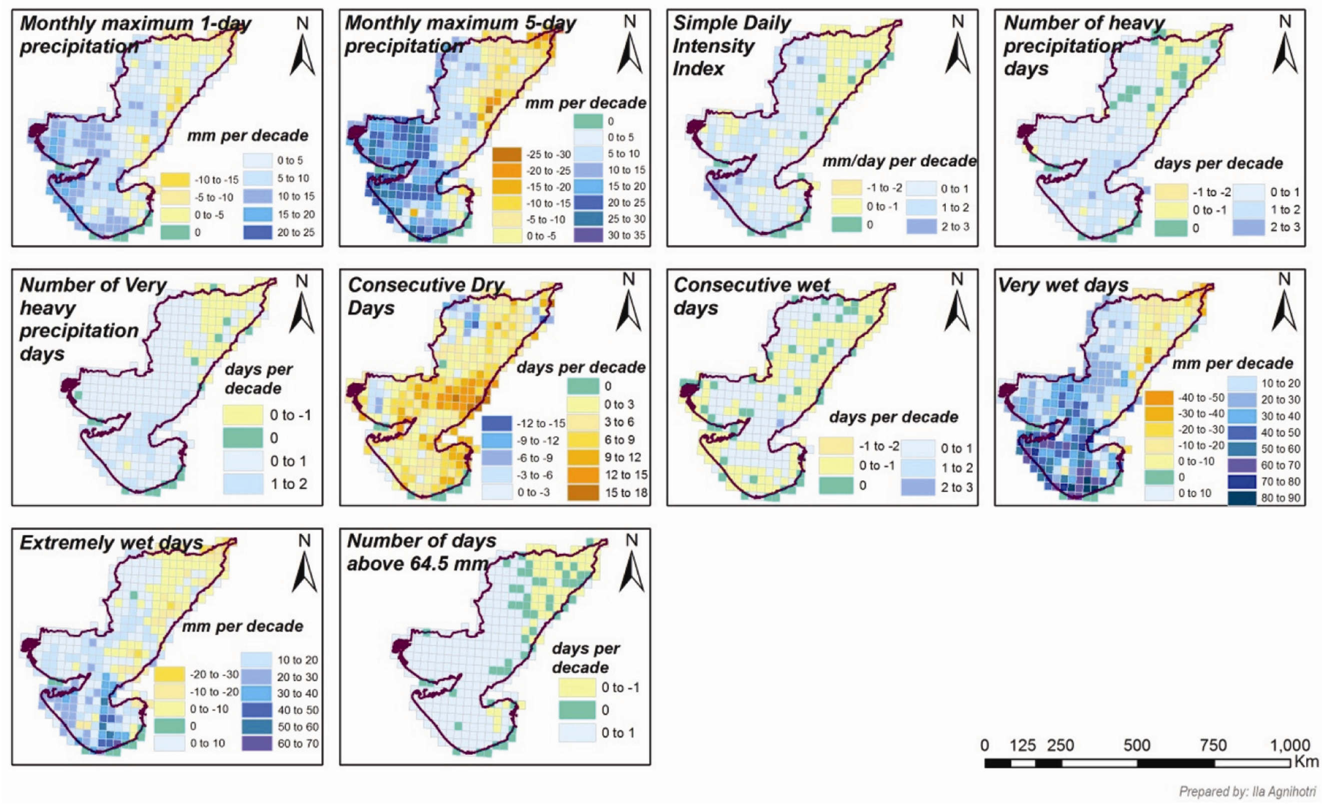

Figure 2. Spatial variations of trend in extreme indices of precipitation in the WFR-KSM basin.

Max T_{min} overall showed an increasing trend with time, except in a group of four grids in the northern part of the basin and a grid in the southeastern coast which showed no trend. Min T_{max} overall showed a variation in trend value with time. The trend was neutral in the three central grids on the Rajasthan–Gujarat border. The grids above this border, all in Rajasthan, showed negative trend and those below the border, all in Gujarat, showed positive trend. The trend ranged from –0.3 to 0.4°C/decade. Min T_{min} overall showed increasing trend which varied spatially with time except in a group of three grids in the eastern part of the basin, two of which showed a slight decreasing trend and one no trend. The slope ranged from –0.1 to 0.7°C/decade. The increase varied spatially.

For cool nights, all grids showed a decreasing trend, except the Aravalli range and Rajasthani Bagar region located at Sirohi-Pali grid, which showed no trend. The decrease was more clustered in grids located in the Kutch peninsula, Gir Range and Kathiawar peninsula (2–4 days per decade) compared to the cluster of grids in the Gujarat Plains and Rajasthani Bagar (0–2 days/decade). For cool days, all grids showed a decreasing trend with time. The decrease ranged from –2.9 to –0.2 days/decade. For warm nights, majority of the grids (78%) showed an increase except seven grids located centrally in the basin. The grids which showed increasing trend were located around a cluster of grids at the centre of basin which showed a decrease with time for warm nights. The slope ranged from –1.2 to 4.5 days/decade. For warm days, all grids showed an increasing trend with time. The grids in eastern and northeastern border of the basin showed lesser increase compared to those located in the western and southwestern border. The rise was observed from 0.6 to 3.6 days per decade.

For warm spell duration indicator (WSDI), all grids showed an increasing trend with time. The grids located in the western and southwestern coastal regions of the basin experience greater increase in warm spell duration compared to other grids. The increase in warm spell varied from 2.1 to 9.7 days/decade. For cold spell duration indicator (CSDI), majority of the grids (81.25%) exhibited a decreasing trend with time. In Gujarat, all grids reflected a decreasing trend, except some part of Banaskantha district. In Rajasthan, the northern grids showed a decreasing trend, and a cluster of grids reflected an increasing trend. The range was from –6 to 1.1 days/decade. The diurnal temperature range (DTR) indicated an increasing trend in 14 grids, 10 were neutral and 8 showed a decreasing trend. The increase was observed in 2 clusters, one in a cluster of 12 grids at the central to northern parts of the basin and another in a two-grid cluster in the southern coastal region of the basin. All the neutral grids were a part of Gujarat. Decreasing trend was exhibited by two clusters of the grids in the southeastern

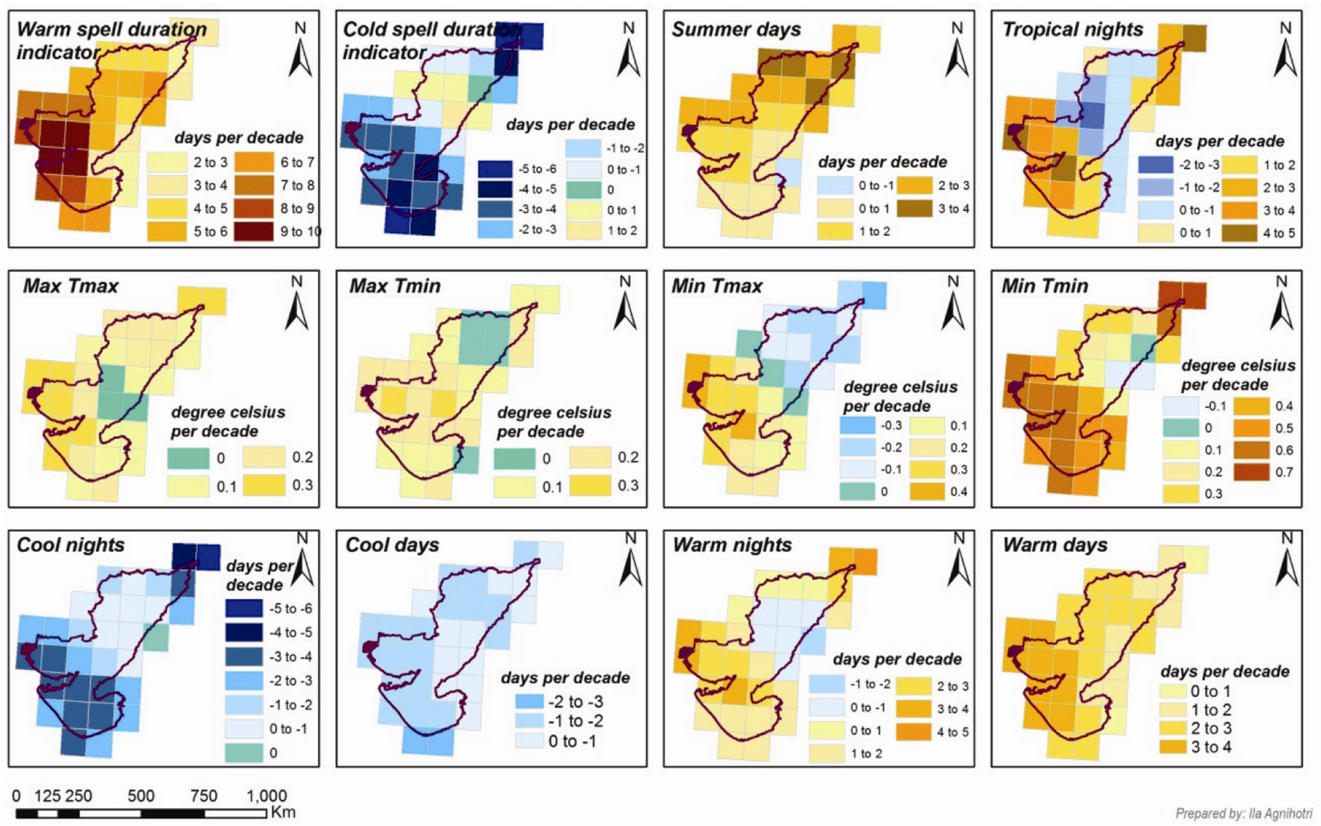

Figure 3. Spatial variations of trend in extreme indices of temperature in the WFR-KSM basin.

and northeastern border areas of the basin. The range of slope was from –0.4°C to 0.2°C/decade. According to criterion of heat wave provided by IMD, 'when actual maximum temperature remains 45°C or more irrespective of normal maximum temperature, heat wave should be declared'. For summer days (SU45), only north-eastern border of the basin exhibited a trend; the remaining areas showed no trend. The slope ranged from –0.1 to 0.7 days per decade.

Trend in extreme indices of precipitation

Monthly maximum 1-day precipitation indicated overall an increasing trend in most of the basin, except at a few places. The trend increased from northeastern to southwestern direction. The slope ranged from –17.1 to 21.6 mm/decade. The monthly maximum consecutive 5-day precipitation suggested an increasing trend in most of the basin, except at a few places. The trend increased from northeastern to southwestern direction. The slope ranged from –29.6 to 34.1 mm/decade.

Simple daily intensity index (SDII) showed an increasing trend in most of the basin, except at a few places. The trend increased from northeastern to southwestern direction. The slope ranged from –1.3 to 2.9 mm/decade. The number of heavy precipitation days also showed an increasing trend in most of the basin, except at a few places. The trend increased from northeastern to southwestern direction. The slope ranged from –1.4 to 2.5 days/decade. The number of very heavy precipitation days indicated an increasing trend in most of the basin, except at a few places in northeastern part of basin which exhibited a decreasing trend. The number of days above 64.5 mm which indicated very heavy precipitation days showed an increasing trend in most of the basin, except at two places where a decreasing trend was observed. The slope ranged from –0.3 to 0.7 days/decade.

The consecutive dry days (CDD) indicated an increasing trend in most of the basin (78.45%), except at a few places where a decreasing trend was observed. The slope ranged from –13.3 to 17.6 days/decade. Consecutive wet days (CWD) showed a balanced increasing and decreasing trend. Around 42% of grids showed a decreasing trend, whereas around 45% of grids showed an increasing trend. The slope ranged from –1.1 to 2.4 days/decade. Very wet days indicated increasing trend in majority of the grids (78.45%). The slope ranged from –48.7 to 110.8 mm/decade. In extremely wet days, majority of the grids (68%) showed increasing trend. The slope ranged from –30 to 60.1 mm/decade. Annual total wet-day precipitation was found to be associated with increasing trend in majority of the grids (78.45%). The trend showed an increase towards southwestern direction, with decreasing trend in northeastern border region and higher values of positive trend in the southwestern region of the basin. The slope ranged from –48.7 to 110.8 mm/decade.

Trend in extreme indices of precipitation and temperature in the basin

The average indices of the basin indicated an increasing trend in rainfall extremes. Max 1-day precipitation amount showed an increase by +4.8 mm/decade. Rx5 day showed an increase by +6.9 mm/decade. Simple daily intensity index showed an increase by +0.5 mm/day/decade. Number of heavy precipitation days showed an increase by +0.6 days/decade. Number of very heavy precipitation days showed an increase by +0.5 days/decade. Number of days above 64.5 mm showed an increase by +0.2 days/decade. Consecutive dry days showed an increase by +4 days/decade. Consecutive wet days did not show any increase or decrease. Very wet days showed an increase by +19.4 mm/decade. Extremely wet days showed an increase by +7.1 mm/decade.

An increasing trend towards warm temperature extremes was also indicated by extreme indices of temperature. Frost days and ice days did not show any trend for the basin. Summer days showed an increasing trend by +1.7 days/decade. Tropical nights showed an increasing trend by +1.1 days/decade. Max T_{max} showed an increase by +0.2°C/decade. Max T_{min} showed increase by +0.1°C/decade. Min T_{max} showed an increase by +0.1°C/decade. Min T_{min} showed an increase by +0.4°C/decade. Cool nights showed a decreasing trend by –2 days/decade. Cool days showed a decreasing trend by –1.2 days/decade. Warm nights showed an increasing tendency by +1.1 days/decade. Warm days showed an increasing tendency by +2.4 days/decade.

WSDI indicated an increasing trend by +6.3 days/decade, whereas CSDI indicated a decreasing trend by –2.1 days/decade. Diurnal temperature range did not show any trend for the basin. Summer days with daily maximum temperature more than 45°C did not show any trend for the basin.

Conclusion

The climate extreme indices were averaged for the WFR-KSM basin. Overall, the average indices indicated an increasing trend towards wetter rainfall extremes, which varies throughout the basin. There was a trend towards warmer temperature extremes and decrease in cold temperature extremes (cool nights, cool days, cold spell duration indicator).

Increasing trend towards warm temperature extremes was indicated by increasing trend in several temperature extreme indices in majority of the grids as summer days, tropical nights, monthly maximum value of daily maximum and minimum temperature, monthly minimum value of daily maximum and minimum temperature, warm nights, warm days and warm spell duration indicator. The decreasing trend in cool nights, cool days and cold spell duration indicator by majority of the grids also indicates the trend towards hotter extremes.

The trend towards wetter precipitation extremes was indicated by increasing trend in several precipitation extreme indices in majority of the grids as Max 1-day precipitation amount, monthly maximum consecutive 5-day precipitation, SDII, number of heavy precipitation days, number of very heavy precipitation days, number of days above 64.5 mm, CDD, very wet days, extremely wet days and annual total wet-day precipitation.

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