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Commentary

Trend analysis of Indian summer monsoon rainfall at different spatial scales

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Abstract

The results obtained from a conventional trend analysis of the Indian summer monsoon rainfall over a larger region are contradicted when analysis is performed at a finer resolution because of spatial variability and heterogeneity in the rainfall pattern. The present study analyzes the trend of summer monsoon rainfall all over India at a finer spatial resolution (1° latitude × 1° longitude) to identify the places that have a significant trend in terms of both rainfall amount and occurrence. The results obtained from this study are compared with those of a recent study by Goswami *et al.* (2006), where trend analysis is performed over a larger region [Central India (CI); 10° latitude × 12° longitude; assumed to be homogeneous in that study]. The increasing trend of occurrence of heavy rainfall and decreasing trend of occurrence of moderate rainfall, as concluded from that study, are contradicted by the present results for some places in CI. The present analysis shows spatially varying mixed responses of global warming toward rainfall occurrence and amounts all over India. The perception of increase in daily rainfall amount and occurrence due to climate change is found to be not correct for some of the regions in India. The possible reason may be the spatial variability of local changes such as rapid urbanization, industrialization and deforestation.

Keywords: **rainfall trend; global change; India**

1. Introduction

The Indian summer monsoon rainfall (ISMR) is a major component of the Asian summer monsoon. India receives about 80% of its total rainfall during the summer monsoon season, from June to September (Sahani *et al.*, 2003). Variation and trends in ISMR have significant social and political impacts as Indian agriculture is largely controlled by ISMR. Therefore, a proper trend analysis of ISMR is required for social and economic planning to assess the impacts of global warming. In a study by Goswami *et al.* (2006), the trend of summer monsoon rainfall over Central India (CI) was analyzed, which was based on the hypothesis of a 'warming environment' and the assumption of homogeneity in summer monsoon rainfall across CI. However, the validity of the assumption was not tested. The present work analyzes the validity of the assumptions made by Goswami *et al.* (2006) and presents trends of ISMR at a finer scale considering spatial variability in the rainfall pattern. The analysis does not limit its spatial extent to only CI; it is performed for the rainfall all over India. Following Goswami *et al.* (2006), the trend of rainfall is computed by linearly regressing rainfall with time. If the regression coefficient value for time is found to be significant at a confidence level of 0.01, the rainfall is considered to have a trend and the coefficient value is reported as being the trend. The data used for the present analysis is the daily gridded rainfall data at 1° × 1° resolutions from the India Meteorological Department (IMD), based on 1803 stations that have at least 90% data availability for the period 1951–2003 [same as that used in Goswami *et al.* (2006)]. A total of 6329 stations (which include those maintained by IMD and individual state governments) cover the country, out of which 1803 stations were used in developing the gridded product. These 1803 stations were chosen on the basis of the constraint that they have at least 90% daily data availability during the 50-year period, so as to minimize temporal inconsistencies. Station data was interpolated to a grid using a weighted sum, which was a variant of a method adopted by the Global Precipitation Climatology Project (Rajeevan *et al.*, 2006). It should also be noted that the density of stations is not uniform throughout India. The present analysis is performed at a spatial resolution of 1° latitude × 1° longitude, and the results are compared with those of Goswami *et al.* (2006), where the analysis was carried out for a spatial resolution of 10° latitude × 12° longitude. As a prerequisite, the following section presents an overview of the monsoon rainfall trend analysis across CI by Goswami *et al.* (2006).

2. Trend Analysis of Summer Monsoon Rainfall over CI

Goswami *et al*. (2006) defined CI as the region extending from 74.5 °E to 86.5 °E and 16.5 °N to 26.5 °N. This region contains 143 grid points of spatial resolution 1° latitude × 1° longitude. To study the impacts of global warming on monsoon rainfall, it is important to isolate the contribution of global warming on extreme events over the monsoon region. As global warming influences the thermodynamic conditions on a very large scale, the aggregate of extreme events over a sufficiently large region is required to be examined so that local effects on trends could be averaged out. This was the physical basis behind selecting a large region; CI, in Goswami *et al*. (2006). CI is also a region where topography does not play a very significant role in producing extreme events. However, in western India, consisting of Western Ghats and eastern India, large mountains influence the extreme events. Therefore, these regions were not included in Goswami *et al*. (2006) for separating out the contribution of global warming from the local orographic influences. The following observations are found in Goswami *et al*. (2006) from the analysis performed over CI:

1. The temporal variance of the daily rainfall anomaly averaged over CI shows a significant increasing trend (at a 0.01 significance level) during 1951–2000.
2. The occurrence of heavy (rainfall >100 mm/day) and very heavy events (rainfall >150 mm/day) over CI shows a significant increasing trend at a 0.01 significance level.

Analysis of monsoon rainfall averaged over a large region is valuable and meaningful for certain purposes. If the objective is to compute year-to-year variation of monsoon lows and depressions, it is not correct to average the rainfall over the whole of India as the spatial scale of monsoon synoptic disturbances is about 1000 km. However, the scale of summer monsoon intraseasonal variability or interannual variability of seasonal mean has much larger spatial scales (of the order of 10 000 km) and hence the CI rainfall average or even all-India average is still quite meaningful. The average rainfall over a large region also represents the water availability for agriculture and hence correlates strongly with the country's agricultural production. This may help the policy makers. However, it should be noted that planning for reservoir operation in a small watershed or in a river basin for irrigation/agriculture requires rainfall information at a local scale, and the average rainfall information over a large region may not be useful here. Such a requirement necessitates the analysis of rainfall at a finer spatial scale for water resources decision making and planning.

While analyzing monsoon rainfall over a large region to identify trends, it is also important to ascertain the computed trend across that region using the field significance test (Livezey and Chen, 1983). To perform the field significance test across CI, first the trend is computed at individual gridpoints for the occurrences of heavy rainfall events (>100 mm/day). The number of stations, which have an increasing trend of occurrences of heavy rainfall events, is used as an input to the field significance test for checking the hypothesis that CI has an increasing trend in occurrences of heavy rainfall. Following Livezey and Chen (1983), the details of the field significance test are discussed in the next subsection.

2.1. Field significance test

In terms of the probability theory, a collection of N independent significance tests (trend analysis of N stations) is perfectly analogous to N tosses of a loaded coin. Instead of Head or Tails, with odds based on the coin load, the outcome for a 0.01 significance level test is test passed (probability equal to 0.01) or test failed (probability equal to 0.99). This can be modeled with a binomial distribution. The field significance test is considered to be passed if the number (M) of individual tests passing (out of N tests), with a significance level 0.01, exceeds a threshold M_0. As per the binomial distribution, the probabilities are exactly 0.23759, 0.34319, 0.24613, 0.11685, 0.04131, 0.0116 and 0.002695 for 0, 1, 2, 3, 4, 5 and 6 passed tests out of 143. Thus, the cumulative probabilities are 0.015 for five or more passed tests and 0.003 for six or more. Therefore, if 143 significance tests are performed, six or more must pass to guarantee at least 99% (in this case 99.7%) significance. Trend analysis is performed at individual stations in CI to compute the trend of occurrences of heavy rainfall events. It is observed that only 4 gridpoints out of 143 have an increasing trend at the 0.01 significance level. Therefore, the field significance test shows that the hypothesis 'Central India has an increasing trend of occurrences of heavy rainfall' fails at the 0.01 significance level.

The analysis, performed by Goswami *et al*. (2006), on summer monsoon rainfall over CI has the following limitations:

1. The field significance test with the hypothesis 'Central India has an increasing trend of occurrences of heavy rainfall' fails, and it contradicts with the conclusions of Goswami *et al*. (2006).
2. The regional heterogeneity test was not carried out in Goswami *et al*. (2006), before considering the large region 'Central India'. A recent analysis by Satyanarayana and Srinivas (2008) clearly shows that places in CI belong to different meteorological regions and therefore CI is not homogeneous.
3. On the basis of the homogeneity assumption for CI, a fixed threshold of 100 mm/day was considered in Goswami *et al*. (2006) to define extreme events. However, a study on regional frequency analysis over India, by Satyanarayana and Srinivas (2008), shows that CI is not homogeneous.

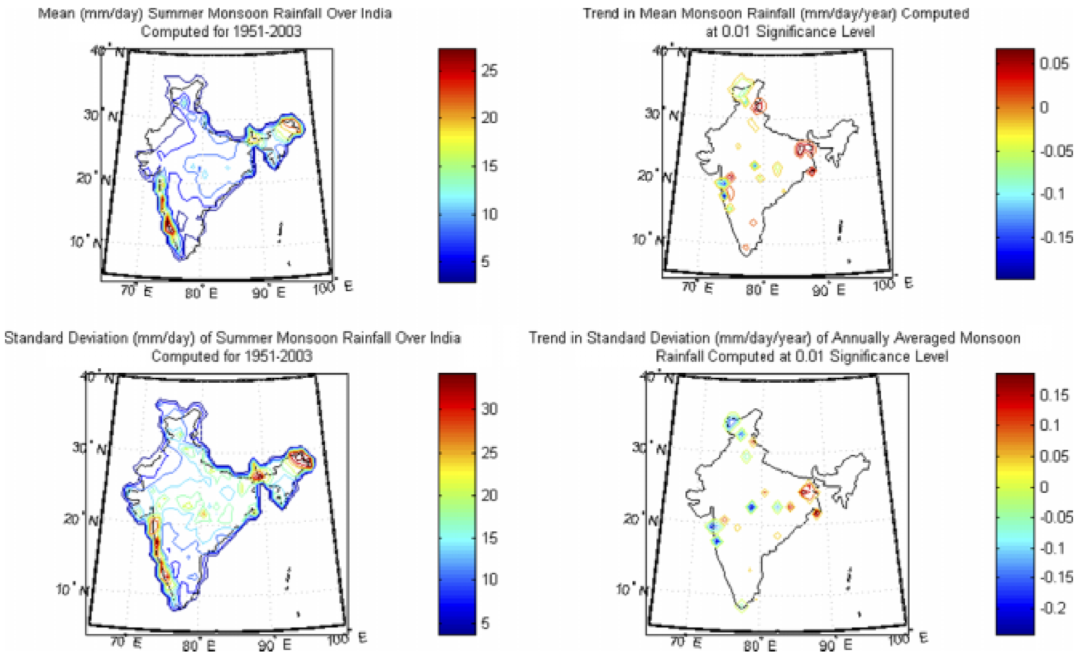

Figure 1. Spatial pattern and trends in mean and standard deviation of mean summer monsoon rainfall.

The present analysis focuses on studying the trend of ISMR at a finer spatial scale (spatial resolution 1° latitude × 1° longitude). The next section presents the details of the analysis.

3. Trend Analysis of Summer Monsoon Rainfall at a Finer Spatial Scale

Although the climatological mean summer monsoon (June, July, August, September) rainfall data of India shows that it has remained stable over the past century with some (Goswami *et al*., 2006) interdecadal variability, it is not always true at a finer spatial scale. Figure 1 shows the spatial variability (in terms of contour plot) of the mean summer monsoon rainfall (for 1951–2003), trend in mean annual summer monsoon rainfall, standard deviation of summer monsoon rainfall and trend in the standard deviation (calculated over the monsoon period of 1 year) of summer monsoon rainfall. Trends in the present report are calculated at the 0.01 significance level. The increasing trends in mean summer monsoon rainfall are observed in a couple of regions around 85 °E to 87.5 °E and 20°N to 27.5 °N (in West Bengal). A significant decreasing trend in the mean annual summer monsoon rainfall is observed in the western coast of India. A few regions in India have significant trends in the annual mean summer monsoon rainfall. Trends are also observed in the standard deviation of daily monsoon rainfall amount at 1° latitude × 1° longitude resolutions. A very high decreasing trend for standard deviation is observed at around 22.5 °N and 78.5 °E, which belongs to CI, and therefore it directly contradicts with the assessment of a high increasing trend in variation of rainfall over entire CI by Goswami *et al*. (2006). Neglecting the spatial variability of rainfall in CI is one of the reasons for such a misinterpretation in Goswami *et al*. (2006). The stability and no trend inferred in Goswami *et al*. (2006) for mean summer monsoon rainfall are not valid at a finer spatial scale (Figure 1(b)). Therefore, analysis of summer monsoon rainfall for a substantially larger region (Sahani *et al*., 2003; Gadgil *et al*., 2004; Krishna Kumar *et al*., 2005; Goswami *et al*., 2006) without considering the spatial variability may misinterpret the actual trend. Analysis with a finer scale may result in a different conclusion. With this background, the following analysis is performed for computing the trend of ISMR at a finer spatial scale (1° latitude × 1° longitude).

Firstly, the analysis is performed in the present study to identify the temporal scale (monthly, weekly or daily) at which significant changes have taken place over the last 53 years. For this purpose, trends of maximum (computed annually) daily, maximum consecutive 7 days, maximum consecutive 15 days and maximum consecutive 30 days monsoon rainfall have been computed and contours plotted. For computation of maximum consecutive 'd' days rainfall annually, a moving window of d days is selected and the rainfall amounts are averaged over the window, i.e. rainfall average for 1 to d days, 2 to '$d + 1$' days, 3 to '$d + 2$' days and so on. The maximum (annually) of these average values is considered as maximum consecutive d days' rainfall. The contour plots are presented in Figure 2. It is observed that most of the places in CI and the west coast have experienced a decreasing trend in maximum consecutive 30, 15 and 7 days rainfall. It is interesting to note that, in the east coast near Bangladesh, there are increasing trends for all the four cases; these are presented in Figure 2. Although a couple of places in CI have experienced an increase in the amount of maximum daily rainfall, a trend is

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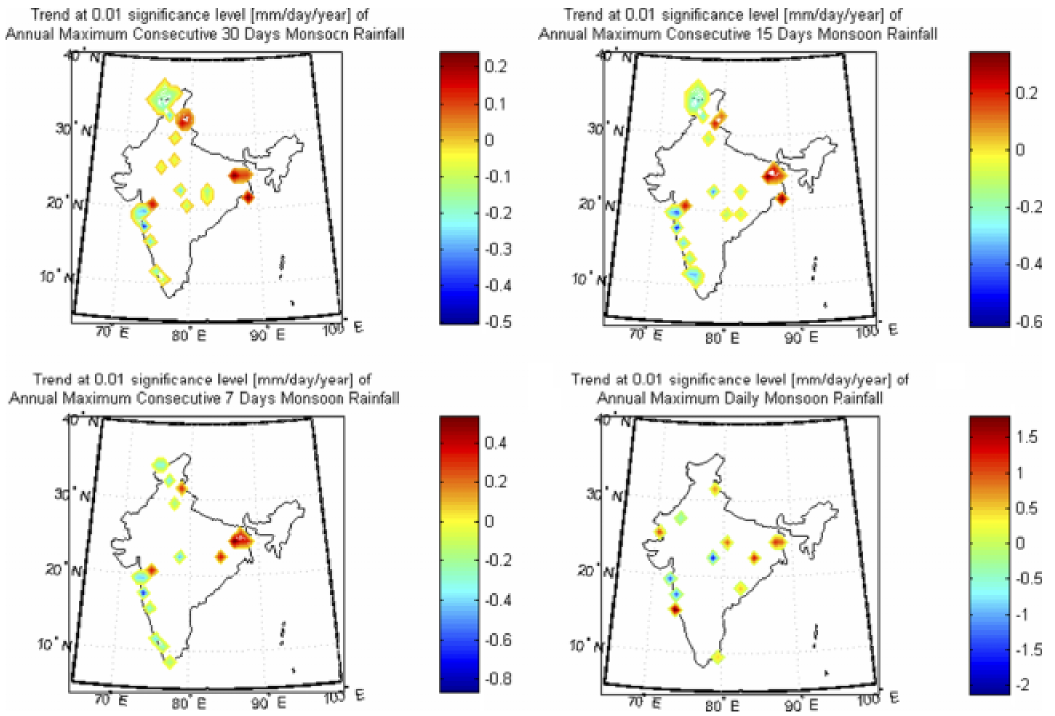

Figure 2. Spatial pattern of trends in maximum consecutive 30 days, maximum consecutive 15 days, maximum consecutive 7 days and maximum daily rainfall.

not observed in most of the places of CI. The region around 22.5 °N and 78.5 °E has experienced a very high decreasing trend in the maximum daily monsoon rainfall. Although it was concluded in Goswami *et al*. (2006) that it is not possible to detect a rainfall trend in a smaller region, trends are clearly visible at a finer spatial scale in the present study, and the result presents more details and a clearer picture of the monsoon rainfall trend and pattern incorporating the spatial variability of trends.

The spatial variability of 25, 50, 75 and 99 percentile monsoon rainfall in India (Figure 3) shows that the rainfall pattern in CI is not homogeneous, which was an assumption in Goswami *et al*. (2006). A recent study (Satyanarayana and Srinivas, 2008) on regional rainfall frequency analysis and regionalization in India shows that places in CI belong to different meteorological regions and the rainfall pattern in CI is significantly heterogeneous. On the basis of this analysis, it can be inferred that the assumption used in Goswami *et al*. (2006) is not valid. The threshold for heavy rainfall in a relatively larger heterogeneous region, CI, was considered to be fixed, 100 mm/day (Goswami *et al*., 2006), which is another reason for the misinterpretation about the trend in monsoon rainfall in that study. The present study focuses on identifying the trend of occurrences of different categories of rainfall all over India considering spatial variation and temporal variations separately to correctly represent the changes under the backdrop of global warming. In identifying the trend, we consider 25 to 75 percentile rainfall in a place (i.e. in a grid of $1° \times 1°$) as moderate rainfall, 75 to 95 percentile rainfall as moderately high rainfall, 95 to 99 percentile rainfall as high rainfall and more than 99 percentile rainfall as extremely high rainfall.

The trends of annual occurrences of moderate, moderately high, high and extremely high rainfalls are plotted in Figure 4. It shows that the trend of occurrences of moderate rainfall has increased in most of the places in CI over 1951–2003. Most of the places in CI have experienced a decreasing trend in the occurrences of moderately high rainfall, which is in agreement with the results of Goswami *et al*. (2006). For high and extremely high rainfall cases, a few places in India have experienced a significant trend. For high rainfall, a couple of places in CI have experienced significant trends that are decreasing in nature. A few locations have increasing trends in terms of occurrences of extremely high rainfall, which matches with the results of Goswami *et al*. (2006), although most of the grid boxes in CI do not have any trend. The location around 22.5 °N and 78.5 °E (in CI) has a significantly high decreasing trend of occurrences of extremely high rainfall. It is interesting to note that this place in CI has experienced a very high decreasing trend in terms of both amount and occurrences of heavy rainfall. The eastern part of India (West Bengal) near Bangladesh has experienced a very high increasing trend in amount and occurrences of extremely high rainfall. Proper management of water resources and floods is required in these places. It should be noted that the density of stations is not uniform throughout India; in particular, the coverage over the eastern part of CI is sparse. The results obtained for eastern India could be at least partially due to sparse data coverage at these locations.

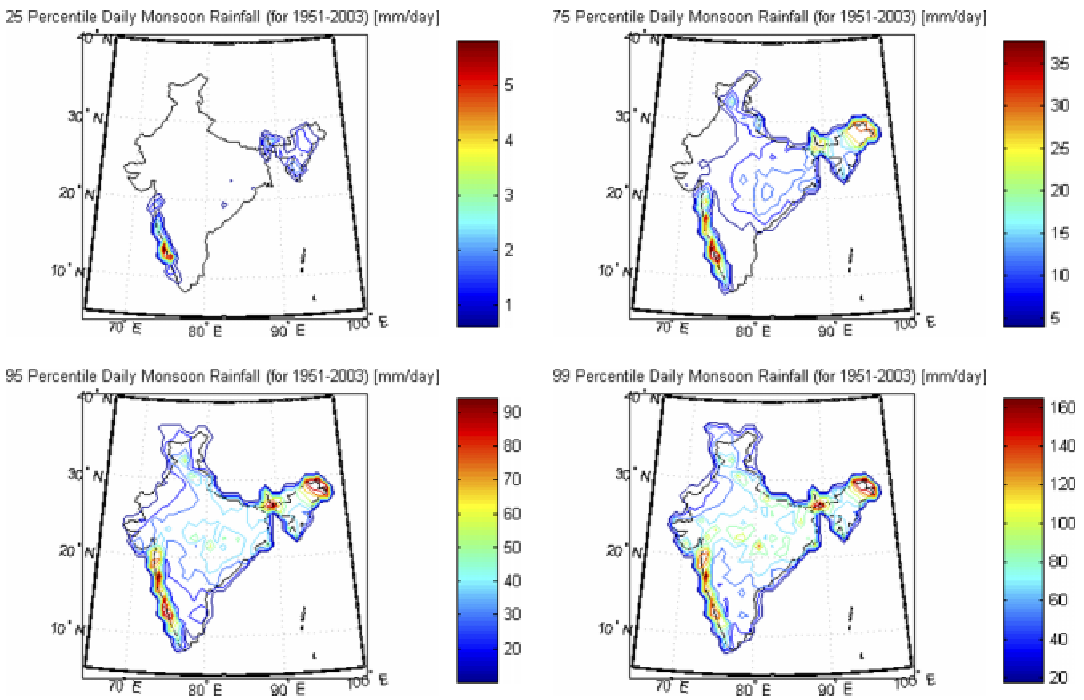

Figure 3. Spatial distribution of 25, 75, 95 and 99 percentile rainfall.

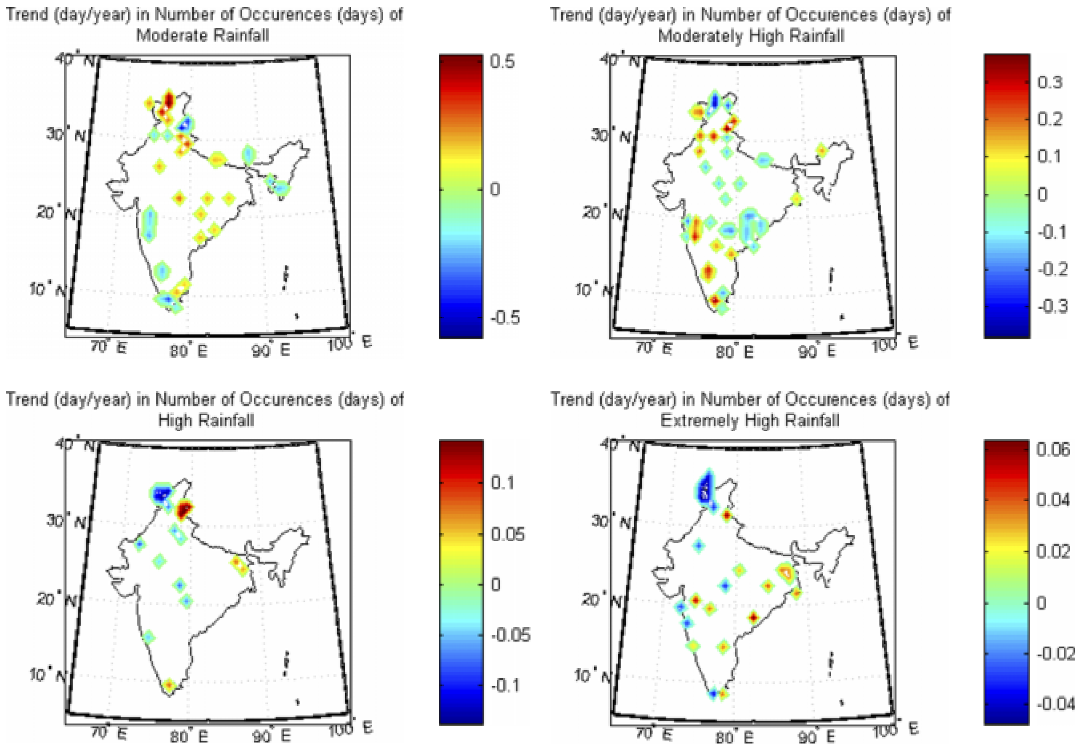

Figure 4. Spatial pattern of trends in the occurrences of moderate, moderately high, high and extremely high rainfall.

ISMR has not only been affected by global warming but may also be substantially affected by local changes such as rapid urbanization, industrialization and deforestation. There are substantial spatial variations in these local changes in India, and, possibly, therefore a varied trend is observed in the summer monsoon rainfall. As these local changes are small-scale phenomena, their impacts on summer monsoon rainfall should be studied at a finer scale. From the present analysis, the following points can be observed:

1. Analysis of ISMR in the backdrop of a changing world should not be studied at a larger scale without any prior analysis at the local scale, as it may result in misleading information for a few places. This may also account for the local changes that affect rainfall.

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2. For performing rainfall analysis over a large region, it is essential to perform a heterogeneity test for validating the assumption of rainfall homogeneity of that region. A field significance test should also be performed to verify the hypothesis.
3. Further analysis of ISMR should include regionalization as the first step, which clusters the places of similar rainfall patterns and trends in the same region (Satyanarayana and Srinivas, 2008). A large-scale analysis, if required, can be performed for these homogeneous regions, resulting from regionalization.

4. Concluding Remarks

The present analysis is motivated by the study of Goswami *et al*. (2006) to analyze trends in Summer monsoon rainfall over India. Certain assumptions in the above-mentioned study were not validated. While validating these assumptions, in the present study, it is observed that the assumptions are not valid because of the large spatial variation of ISMR. The analysis is reperformed at a finer spatial scale without considering the assumptions, and it results in a different outcome for a few places. It can be concluded from the study that the conventional method of representing ISMR using a single variable has some limitations and may result in an erroneous outcome for a few places. The results of local-scale studies may not match with those of large-scale analysis. India, being a developing country, is characterized by local-scale changes, viz., population growth and urbanization, which have significant impacts on the summer monsoon rainfall pattern. These local changes are obviously not uniform all over India. Therefore, results at a finer scale considering spatial variability are more important and reliable for further use of rainfall data in hydrological applications and water resources management. In the present study, places in India, which have experienced a significant trend in monsoon rainfall, have been identified. Outcomes of this study will be helpful in further hydrological analysis, which are essentially at finer scales and can be used for water availability studies for water resources management.

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