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Uncertainty in drought characterization using gridded and station datasets from the India Meteorological Department in the Krishna River Basin, India

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Abstract: The accessibility of long-term datasets of good quality across large regions remains a challenge. Generally, gridded datasets are used to estimate drought as station datasets are not readily available. Drought is generally assessed using gridded datasets, as station-based observations are often unavailable or inaccessible. However, gridded datasets have some limitations as they are developed using interpolation techniques. Therefore, the gridded and station datasets (precipitation and temperature) from the India Meteorological Department (IMD) have been studied for drought estimation in the Krishna River Basin of India from 1980-2019. The Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) were used at 3-month timescales to characterize meteorological drought. The drought characteristics such as average drought duration, severity, and the total number of drought months were obtained using the run theory. Further, the statistical parameters were checked at seasonal (south-west and north-east monsoon) and annual scales for both the datasets to better understand their uncertainty. It was observed that the average annual rainfall of the gridded data was relatively higher than that of station data. Also, the gridded dataset did not capture all the moderate, severe, and extreme drought events. It may be simply because the gridded rainfall has been estimated using interpolation of observed rainfall in the stations in the vicinity of the given grids. On the other hand, the station datasets captured most of the drought events more realistically. Thus, the station datasets yield a more realistic assessment of drought events compared to that from gridded datasets. Therefore, the station datasets should be preferred over gridded ones for better accuracy of drought predictions and early warning systems.

Key words: Meteorological drought; gridded datasets; station datasets; SPI; SPEI; Krishna basin.

1. INTRODUCTION

Due to global warming and human activities, there has been an increase in extreme climatic events such as floods and droughts in recent years, impacting agriculture, ecosystem, and water resources (Gupta et al., 2024a, 2024b; AghaKouchak et al., 2020; Wu et al., 2020). Drought is a natural hazard and India is among the most affected drought countries in the world (Mishra & Singh, 2011). Drought often develops slowly but severely impacts agriculture, environment, and human livelihood (Gupta et al., 2024, 2025, 2026; Van Loon et al., 2016). Drought frequently occurs at different regions in India, and around 94 million hectares of land areas are susceptible to drought (Gupta et al., 2023, 2025). In 2002 alone, drought reduced food grain production by almost 38 million tons in India, thus resulting in a decline in agricultural GDP by 3.2 per cent (Gupta et al., 2024; Rathore et al., 2014). Droughts are more frequent in India in Indo-Gangetic plains, Maharashtra and coastal South India (Mallya et al., 2016). Climate and weather data information are important to understand the impacts of drought on various facets of agriculture production. Long-term precipitation and temperature datasets are required to study the impacts of climate change (Piyoosh & Ghosh, 2016). However, the availability of long-term meteorological observatory datasets at any region remains a challenge, as most of the station dataset lack spatio-temporal continuity over longer period (Van Wart et al., 2015). Also, the observed station datasets which are directly measured are often restricted and limited in access (Hughes et al., 2009). Gridded weather datasets are easily available and are developed from spatial interpolation of station observation, satellite remote sensing, reanalysis products, or combinations of these data sources, satellite-based datasets, which provide important weather information for any location. Gridded precipitation datasets are useful for climate studies, including investigating climatic change and variability (Dai et al., 1997; Sen Roy & Balling, 2004). Indian Meteorological Department (IMD) and various other national weather agencies provide gridded precipitation and temperature datasets for extended durations, which are extensively used. The gridded datasets such as precipitation and temperature are continuous and are used for locations which lacks observational datasets. However, gridded datasets have some inherent limitations as they are produced using interpolation technique. Therefore, to better understand the characteristics and constraints of gridded datasets, the gridded and observed station datasets need to be checked and compared for the dataset reliability for the computation of meteorological drought and its characteristics.

Many studies have conducted the comparison of different meteorological datasets which are generated by various sources (Klein Tank et al., 2002; Pai et al., 2014; Chakraborty et al., 2018; Krajewski et al., 2000). The twentieth century yielded similar trends for both forms of data, according to comparisons of monthly gridded precipitation datasets and station (rain gauge) observations (Klein Tank et al., 2002). Additionally, monthly data produced from satellite observations and interpolated climatological datasets exhibit a strong link (Krajewski et al., 2000). Pai et al. (2014) developed daily gridded IMD4 dataset at 0.25° × 0.25° resolution over India by comparing with 4 other existing daily gridded rainfall datasets of different resolutions and time periods. For this purpose, 6995 daily rainfall records from rain gauge stations were used after quality control. It was found that the climatological and variability characteristics of the rainfall across India that produced from IMD4 were equivalent to the datasets already used for daily gridded rainfall. However, just a few research have compared station data with gridded precipitation datasets. Chakraborty et al. (2018) compared temperature and rainfall data between gridded data obtained from IMD and manually observatory data over Indo-Gagentic plain of India. The monthly values as well as daily extremes were compared and it was observed that the gridded datasets explained the variations of station data, thus it was concluded that the gridded datasets can be directly used if the observed station datasets are not accessible for any region.

In the present study, a comparative analysis of gridded datasets such as precipitation, maximum and minimum temperature with that of manually observatory station datasets was conducted to check the datasets reliability for the computation of meteorological drought characteristics in the semi-arid Krishna River Basin of Peninsular India.

2. MATERIALS AND METHODS

2.1 Study area

The Krishna River Basin (KRB) is the second-largest River Basin of Peninsular India, covering the states of Andhra Pradesh, Karnataka, Maharashtra and Telangana has been taken for the present study. The total area of the Krishna River Basin is 2,58,948 km^2 which is nearly 8% of the total geographical area of India. The Krishna basin lies between 13^{0}5’58” - 19^{0}24’35” N and 73^{0}20’28” - 81^{0}0’43” E. The Krishna River originates from the Western Ghats and flows over a length of 1400 km to the Bay of Bengal. The Krishna River Basin exhibits mainly a semi-arid climate with an annual average rainfall of 780 mm, out of which 90% occurs during the South-West Monsoon from June to September. Some districts of Andhra Pradesh, Karnataka, Maharashtra and Telangana are mostly susceptible to drought.

2.2 Data

The daily gridded precipitation (0.25° x 0.25°) datasets and gridded maximum and minimum temperature (1° x 1°) datasets were obtained from the Indian Meteorological Department (IMD) for the study period 1980-2019 (Pai et al., 2014; Srivastava et al., 2009). It is important to bring all the datasets (precipitation, maximum and minimum temperature) under the same resolution both spatially and temporally for the estimation of drought, and hence all the datasets are converted to (0.5° x 0.5°) using the bilinear interpolation technique. The datasets were further aggregated into monthly datasets to be used as primary input data to calculate the Standardised Precipitation Index (SPI) and the Standardised Precipitation Evapotranspiration Index (SPEI). The monthly precipitation and monthly mean temperature data of 21 rain-gauge stations were also obtained from the Indian Meteorological Department (IMD) Data Supply Portal (https://dsp.imdpune.gov.in). The location map of the Krishna River Basin showing gridded data points and location of rain-gauge stations is shown in Figure 1. All the analysis was carried out using open-source R software and its IDE R-Studio (R Studio Team, 2015; Team, 2017). The data duration and the geographical coordinates corresponding to the 21 rain-gauge stations obtained from IMD are given in Table 1.

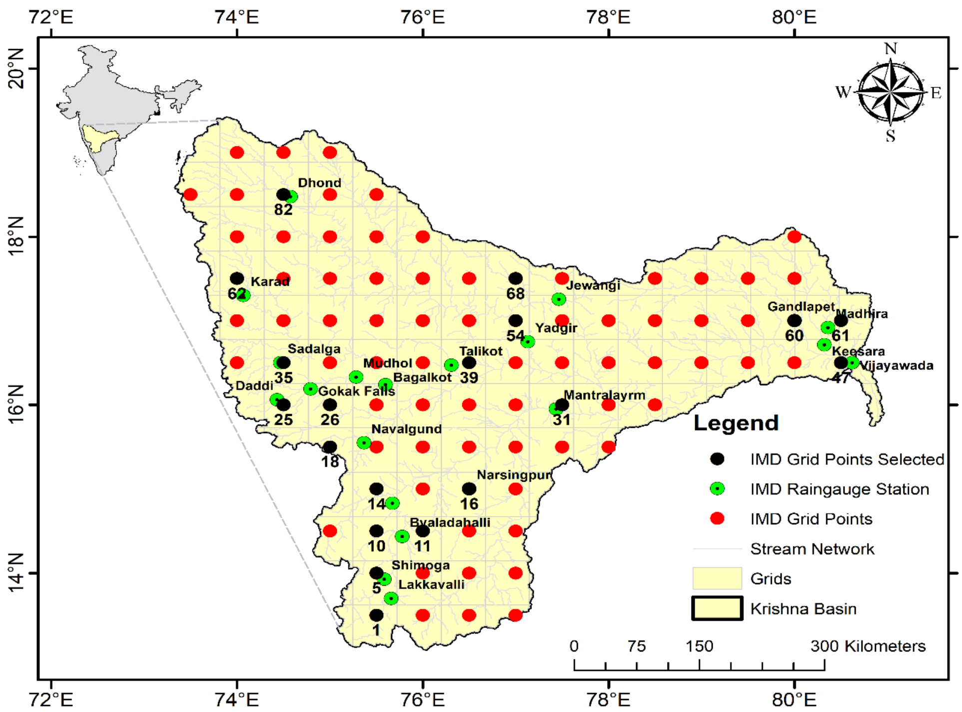

Figure 1. Location map of Krishna River Basin showing grid points and rain-gauge stations.

Table 1. Location and duration of station data used in this study

Sr. No.	Location	Latitude	Longitude	Data Duration
1	Dhond	18° 28' 26.04" N	74° 34' 35.04" E	1980-2019
2	Gokak Falls	16° 11' 24" N	74° 47' 29.04" E	1980-2019
3	Karad	17° 18' 0" N	74° 4' 0.12" E	1980-2019
4	Madhira	16° 55' 5.16" N	80° 21' 32.04" E	1980-2019
5	Navalgund	15° 33' 0" N	75° 22' 0.12" E	1980-2019
6	Shimoga	13° 55' 36.84" N	75° 35' 6" E	1980-2019
7	Talikot	16° 28' 14.88" N	76° 18' 29.88" E	1980-2019
8	Yadgir	16° 45' 0" N	77° 7' 48" E	1980-2019
9	Byaladahalli	14° 26' 2.04" N	75° 46' 46.92" E	1980-2019
10	Gandlapet	17° 0' 0" N	80° 0' 0" E	1980-2019
11	Haralahalli	14° 49' 50.16" N	75° 40' 27.84" E	1980-2019
12	Jewangi	17° 15' 15.84" N	77° 27' 46.08" E	1980-2019
13	Keesara	16° 42' 52.92" N	80° 19' 13.08" E	1980-2019
14	Mantralym	15° 57' 0" N	77° 25' 59.88" E	1980-2019
15	Sadalga	16° 30' 0" N	74° 28' 0.12" E	1980-2019
16	Vijayawada	16° 30' 0" N	80° 37' 12" E	1980-2019
17	Bagalkot	16° 14' 24" N	75° 36' 0" E	1980-2019
18	Mudhol	16° 19' 48" N	75° 16' 48" E	1980-2019
19	Daddi	16° 3' 36" N	74° 25' 48" E	1980-2019
20	Lakkavalli	13° 42' 0" N	75° 39' 36" E	1980-2019
21	Narsingpur	15° 0' 0" N	76° 30' 0" E	1980-2019

2.3 Evaluation methods

The methodological framework of the study consists of five significant steps:

1. The monthly precipitation and temperature records were used to estimate the SPI and SPEI at a 3-month timescale.
2. The drought characteristics such as the average drought duration (in months), average drought severity, and the total number of drought months was computed using the run theory approach.
3. The correlation between the IMD grid point data and their corresponding closest rain-gauge station data was evaluated using a stream network where the grids and stations fall near each other.
4. A comparative analysis was done between the gridded and station datasets at a 3-month timescale using statistical parameters such as coefficient of variation, mean, median, maximum and minimum value, standard deviation and skewness.
5. Finally, the comparison of results was done based on the total number of drought months at seasonal and annual scale, moderate, severe and extreme drought categories.

The methodology used in this study is presented in flow chart as shown in Figure 2.

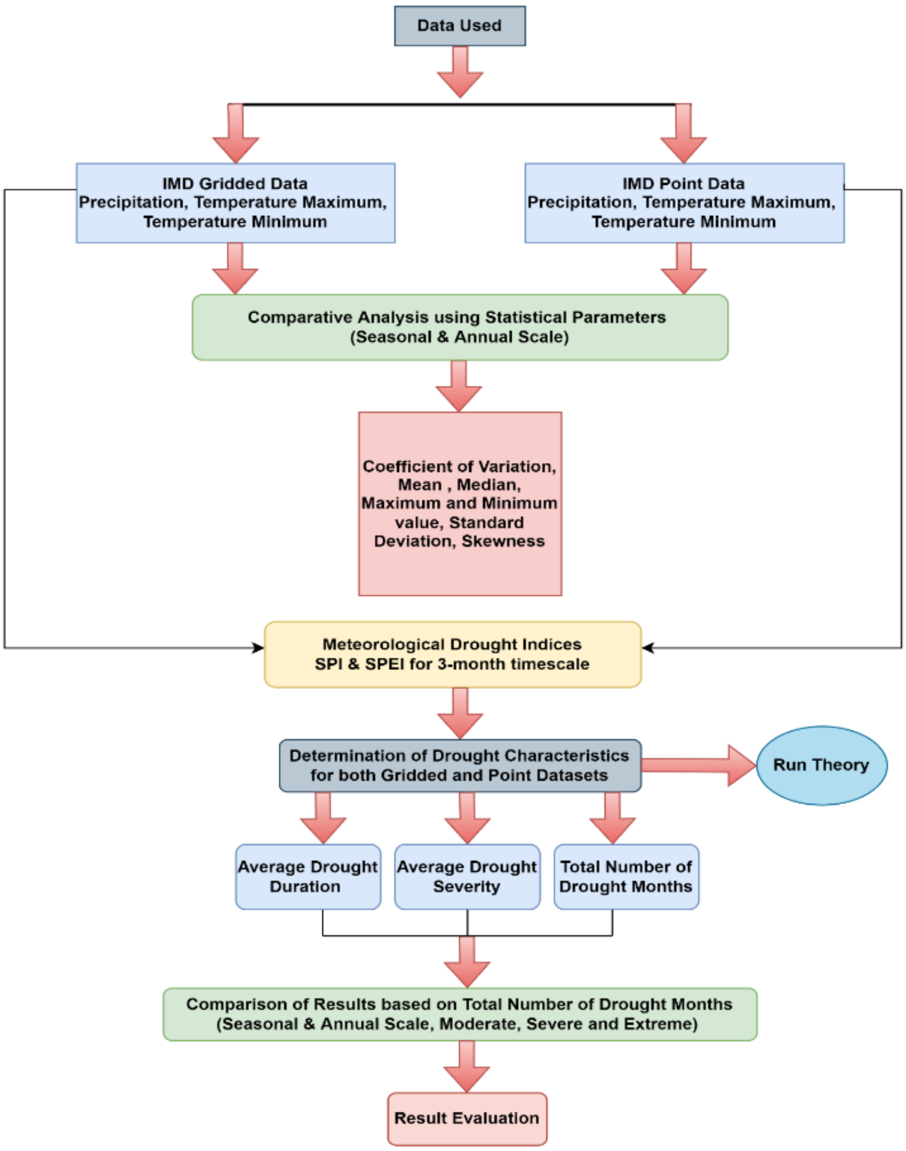

Figure 2. Flowchart of the proposed methodology

2.4 Drought indices

2.4.1 Standardised Precipitation Index (SPI)

The SPI is the most widely used drought index for identifying meteorological drought (McKee et al., 1993). The SPI for any region is determined based on the extended precipitation data (at least 30 years). The data is fitted to a specific probability density function like exponential, gamma, log-normal or Weibull, which is further transformed to a normal distribution with a mean of zero and standard deviation one (Vicente-Serrano et al., 2010). In the present study, the monthly precipitation data was fitted into a two-parameter gamma distribution function and is given by Equation 1. The gamma distribution effectively captures the characteristics over a wide range of hydro-climatic conditions as precipitation is a non-negative and positively skewed variable. Owing to its flexibility and demonstrated performance in representing precipitation data, the gamma distribution is the standard probability distribution recommended for SPI estimation (Mckee et al., 1993).

$$f(X;\alpha,\beta) = \frac{1}{\beta^{\alpha} \int_0^{\alpha} X^{\alpha-1} e^{-X} dX} X^{\alpha-1} e^{-X/\beta}, \text{ for } X > 0 \tag{1}$$

where: x is the monthly precipitation, α and β are the shape and scale parameter of the gamma distribution function. The gamma probability function was further transformed to a standard normal variate with mean zero and standard deviation one.

2.4.2 Standardised Precipitation Evapotranspiration Index (SPEI)

The SPEI (Vicente-Serrano et al., 2010) was suggested for monitoring meteorological drought. The calculation process of SPEI is similar to SPI computation, but it also considers potential evapotranspiration. Using the monthly precipitation (P) and potential evapotranspiration (PET), the water balance (WB) is calculated using Equation 2.

$$WB = P - PET \tag{2}$$

The PET was calculated using the Hargraves equation, which requires maximum temperature, minimum temperature and latitude as its input. The water balance was fitted to a three-parametric log-logistic distribution and is given by Equation 3.

$$f(X;\alpha,\beta,\gamma) = \frac{(1+\frac{\gamma(X-\alpha)}{\beta}^{-(\frac{1}{\gamma}+1)}}{\beta\left[\left(1+\frac{\gamma(X-\alpha}{\beta}\right)^{-\frac{1}{\gamma}}\right]^2} \tag{3}$$

where: x is the water balance (WB), and α, β, and γ are the location, scale, and shape parameters. The log-logistic probabilities were then transformed into a standard normal distribution. Various drought indices have different ranges for categorizing the severity of the drought of an event. Based on the SPI and SPEI indices range, the drought is generally categorized into moderate, severe, and extreme categories depending upon the estimated index values. The adopted range of index values for the drought categorization is given in Table 2.

2.5 Drought characterization

The Run Theory captures the start and end of the drought period within a specific drought threshold (Yevjevich, 1969). The Run Theory method is used to identify the drought duration, severity, frequency, and interval for a given threshold value. This study considers a series of consecutive meteorological drought indices values lower than -1 to define a run (Wu et al., 2021). The drought duration is the time between the start and end of a drought event. The drought severity is the absolute value of SPI or SPEI series during a drought event. In the present study, the SPI and SPEI index is used to identify the meteorological drought characteristics like the average drought duration, severity, and the total drought months (i.e., the drought months falling under moderately, severely, and extremely drought categories with values -1 or less).

Table 2. Drought Classification of SPI & SPEI values (McKee et al., 1993; Vicente-Serrano et al., 2010)

Drought Categories	**Drought Range**	
	SPI	**SPEI**
Extreme Drought	≤ -2.0	≤ -2.0
Severe Drought	-1.99 to -1.5	-1.99 to -1.5
Moderate Drought	-1.49 to -1.0	-1.49 to -1.0
Normal	-0.99 to 0.99	-0.99 to 0.99
Moderate Wet	1.0 to 1.49	1.0 to 1.49
Severe Wet	1.5 to 1.99	1.5 to 1.99
Extreme Wet	≥ 2.0	≥ 2.0

2.6 Statistical analysis

To check the results obtained from gridded and point datasets, for reliable estimation of drought and its characteristics, the statistical analysis has been carried out. The statistical parameters used are coefficient of variation (*CV*), mean value (μ), maximum value, minimum value, median value, standard deviation (σ), and skewness ($\tilde{\mu}_3$) are calculated using the equation given below.

$$\mu = \frac{\sum_{i=1}^{i=n} Xi}{N} \tag{4}$$

$$\sigma = \sqrt{\frac{\sum (Xi - \mu)^2}{N}} \tag{5}$$

$$CV = \frac{\sigma}{\mu} \tag{6}$$

$$\widetilde{\mu_3} = \frac{\sum_i^N (Xi - \mu)^3}{(N-1)\times \sigma^3} \tag{7}$$

where: N is the sample size, x_i is the value of sample size, μ is the mean value of sample, σ is the standard deviation, *CV* is the coefficient of variation and $\tilde{\mu}_3$ is the skewness of the sample.

3. RESULTS AND DISCUSSION

The meteorological drought and its characteristics were estimated using the SPI and SPEI at 3-month timescale. The meteorological variables, namely precipitation, maximum and minimum temperature, from gridded datasets of IMD were analysed and compared with that of the observed station datasets obtained from IMD in the semi-arid Krishna River Basin of Peninsular India. For the comparison, 21 IMD rain-gauge stations nearest to IMD grid points falling on the stream networks were considered. The name of the rain-gauge station and the corresponding grid points (as shown in Figure 1) are given in Table 3.

3.1 Coefficient of determination

The coefficient of determination (R^2) value between the gridded precipitation and the corresponding rain-gauge station precipitation varies from 0.044 to 0.925. The number of R^2 value between the gridded precipitation and the corresponding rain-gauge station precipitation in the range of (0.75 and above) was found to be 4, in the range of (0.7 - 0.75) was found to be 3, in the range of (0.6 - 0.7) was found to be 2, in the range of (0.5 - 0.6) was found to be 4, whereas in the range of (0.5 and below) was found to be 10.

Table 3. Rain-gauge stations and their nearest grid points

Sr. No.	Grid	Station
1	Grid 1	Lakkavalli
2	Grid 5	Shimoga
3	Grid 10	Byaladahalli
4	Grid 11	Haralahalli
5	Grid 14	Haralahalli
6	Grid 16	Narsingpur
7	Grid 18	Navalgund
8	Grid 25	Daddi
9	Grid 25	Gokak Falls
10	Grid 26	Gokak Falls
11	Grid 26	Mudhol
12	Grid 26	Bagalkot
13	Grid 31	Mantralym
14	Grid 35	Sadalga
15	Grid 39	Talikot
16	Grid 47	Vijayawada
17	Grid 54	Yadgir
18	Grid 60	Gandlapet
19	Grid 61	Keesara
20	Grid 61	Madhira
21	Grid 62	Karad
22	Grid 68	Jewangi
23	Grid 82	Dhond

Figure 3 shows the correlation plots between gridded precipitation and their corresponding rain-gauge station precipitation at six locations. It was observed that the gridded and point datasets for the corresponding period have a maximum coefficient of determination (R^2) value in the order of about 0.925.

3.2 Annual and seasonal precipitation analysis

To better understand the reliability of gridded dataset with respect to station dataset, the statistical parameters like coefficient of variation, mean, median, maximum, and minimum value, standard deviation, and skewness were checked at seasonal (south-west and north-east monsoon) and annual scale for all the grid points and their corresponding rain-gauge stations at 3-month timescales as shown in the form of boxplots from Figure 4 to 6, respectively.

From Figure 4 (a-f), it was observed that at seasonal scale i.e., for south-west monsoon, the mean value for gridded datasets varied from 353.42 mm to 1664 mm, whereas for station datasets it varied from 281.15 mm to 1061.07 mm. The median value for gridded datasets varied from 323.37 mm to 1591.85 mm, whereas for station datasets it varied from 274.35 mm to 1032 mm. The maximum value for gridded datasets varied from 531.58 mm to 4156.38 mm, whereas for point datasets it varied from 553.8 mm to 2690.6 mm. The minimum value for gridded datasets varied from 33.5 mm to 688.05 mm, whereas for point datasets it varied from 21.3 mm to 708 mm. Thus, it can be stated that in case of south-west monsoon, the gridded rainfall dataset shows notably higher rainfall compared to the observed station rainfall at corresponding rain gauge station. The standard deviation value for gridded datasets varied from 99.02 mm to 901.23 mm, whereas for station datasets it varied from 107.98 mm to 576.45 mm. The coefficient of variation value for gridded datasets varied from 0.28 to 1.1, whereas for station datasets it varied from 0.18 to 0.56. Also, the skewness value for gridded datasets varied from 0.08 to 2.85, whereas for station datasets it varied from -0.19 to 1.61.

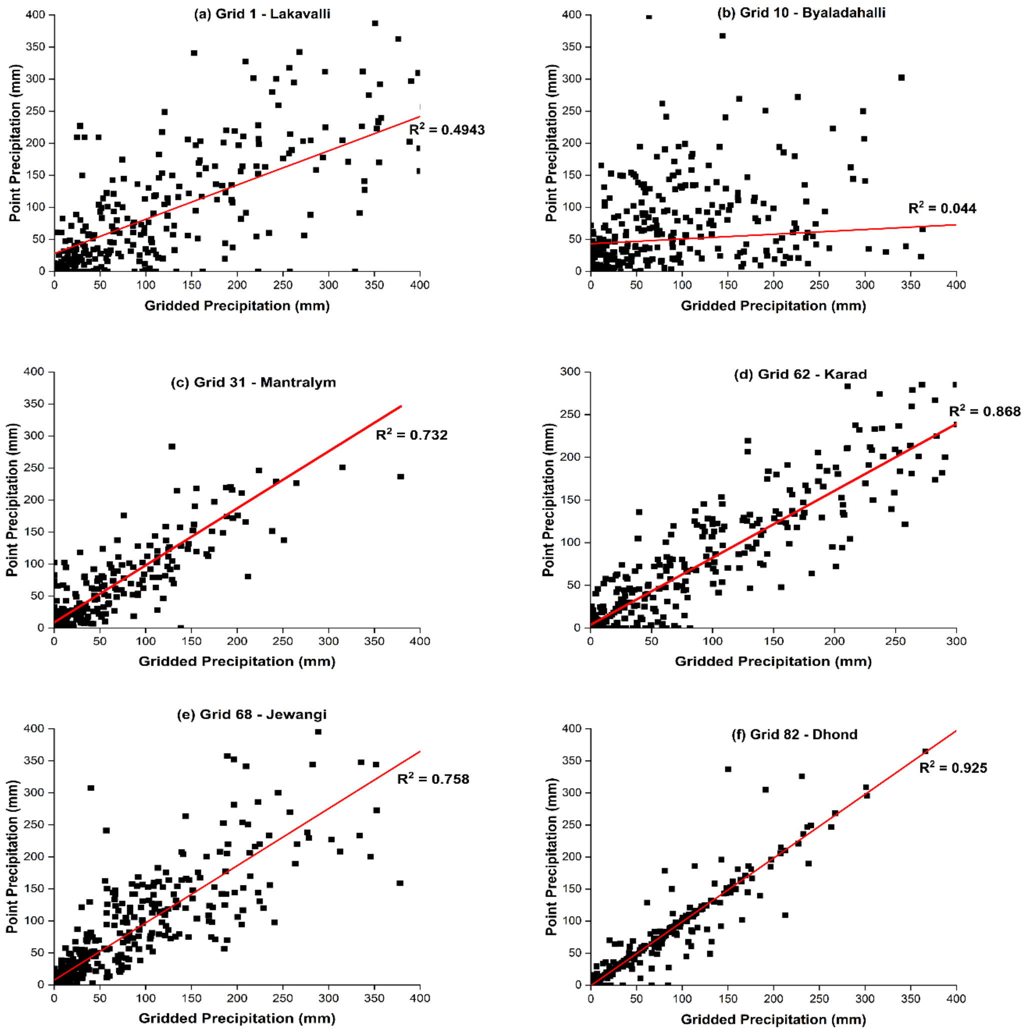

Figure 3 (a-f). Coefficient of determination (R^2) value between gridded precipitation and station precipitation

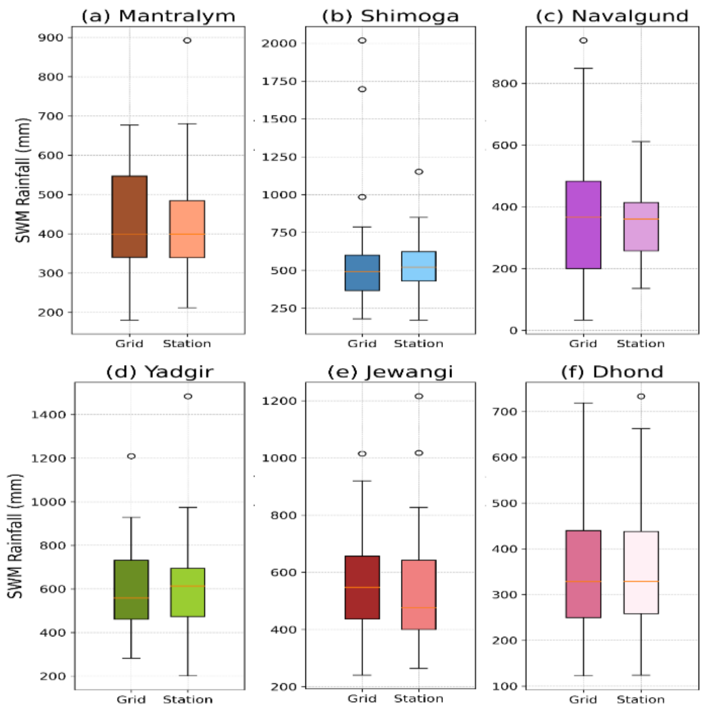

Figure 4 (a-f). Boxplot showing statistical parameters at south-west monsoon (SWM) for grid points and their corresponding rain-gauge stations at six locations

The boxplots for all the other grid points and their corresponding rain-gauge stations at south-west monsoon are shown in the supplementary Figure (S1-S3). From Figure S1 (g–l), it was observed that at the seasonal scale, i.e., during the south-west monsoon, substantial spatial variability exists between the gridded and station-based rainfall datasets across the selected rain gauge stations. The gridded rainfall generally exhibited higher rainfall values than the corresponding station observations at Lakkavalli and Gokak Falls, whereas the station rainfall was considerably higher than the gridded rainfall at Narsingpur. At Mudhol and Bagalkot, the distributions of rainfall from the gridded and station datasets were relatively comparable, while at Haralahalli, the station dataset generally exhibited higher rainfall values than the gridded dataset. The median rainfall was approximately 1590 mm and 900 mm for the gridded and station datasets, respectively, at Lakkavalli; approximately 390 mm and 1030 mm at Narsingpur; approximately 475 mm and 275 mm at Gokak Falls; approximately 325 mm and 320 mm at Mudhol; approximately 315 mm and 305 mm at Bagalkot; and approximately 340 mm and 400 mm at Haralahalli. The boxplots also indicate considerable differences in the spread and occurrence of extreme rainfall values between the gridded and station datasets. In particular, Lakkavalli and Gokak Falls show several high-rainfall outliers in the station and gridded datasets, respectively. Narsingpur also exhibits a pronounced difference in rainfall magnitude between the two datasets, with substantially higher values for the station observations. Therefore, Figure S1 demonstrates that the agreement between gridded and station rainfall datasets varies considerably from one station to another during the south-west monsoon, highlighting the importance of station-specific evaluation of gridded rainfall products.

From Figure S2 (m–r), it was observed that at the seasonal scale, i.e., during the south-west monsoon, considerable differences exist between the gridded and station-based rainfall distributions across the selected stations. The median rainfall for the gridded and station datasets was approximately 395 mm and 360 mm at Talikot, 810 mm and 645 mm at Madhira, 665 mm and 640 mm at Vijayawada, 600 mm and 280 mm at Byaladahalli, 460 mm and 665 mm at Daddi, and 385 mm and 410 mm at Sadalga, respectively. The gridded dataset generally exhibited higher median rainfall than the station dataset, except at Daddi and Sadalga, where the station datasets showed higher median values. Considerable differences in rainfall variability and extreme values were also observed, particularly at Byaladahalli, which exhibited several high-rainfall outliers in the gridded dataset. Overall, Figure S2 demonstrates that the agreement between gridded and station rainfall datasets varies considerably among stations, emphasizing the need for station-specific evaluation of gridded rainfall products during the south-west monsoon.

From Figure S3 (s–w), it was observed that at the seasonal scale, i.e., during the south-west monsoon, substantial differences exist between the gridded and station-based rainfall distributions across the selected stations. The median rainfall for the gridded and station datasets was approximately 390 mm and 400 mm at Haralahalli, 780 mm and 320 mm at Gandlapet, 770 mm and 590 mm at Keesara, 720 mm and 565 mm at Karad, and 320 mm and 275 mm at Gokak Falls, respectively. The gridded dataset generally exhibited higher median rainfall than the station dataset, except at Haralahalli, where the station median was slightly higher. Considerable differences in rainfall variability and extreme values were also evident, particularly at Haralahalli and Gandlapet, where the gridded dataset showed high-rainfall outliers. Overall, Figure S3 demonstrates that the agreement between gridded and station rainfall datasets varies considerably among stations, highlighting the need for station-specific evaluation of gridded rainfall products.

Also, from Figure 5 (a-f), it was observed that at seasonal scale i.e., for north-east monsoon, the mean value for gridded datasets varied from 99.28 mm to 220.64 mm, whereas for station datasets it varied from 96.45 mm to 257.53 mm. The median value for gridded datasets varied from 80.46 mm to 208.86 mm, whereas for station datasets it varied from 68.86 mm to 226.8 mm. The maximum value for gridded datasets varied from 251 mm to 560.17 mm, whereas for station datasets it varied from 232 mm to 546 mm. The minimum value for gridded datasets varied from 1.09 mm to 39.68 mm, whereas for station datasets it varied from 1.4 mm to 48.2 mm. Thus, it can be stated that in case of north-east monsoon, there is no significant difference between the gridded rainfall dataset compared to the observed station rainfall at corresponding rain gauge station. The standard deviation value for gridded datasets varied from 63.52 mm to 141.14 mm, whereas for station datasets it varied from 57.12 mm to 153.5 mm. The coefficient of variation value for gridded datasets varied from 0.56 to 0.83, whereas for station datasets it varied from 0.54 to 0.9. Also, the skewness value for gridded datasets varied from 0.42 to 2, whereas for station datasets it varied from -0.03 to 1.88.

The boxplots for all the other grid points and their corresponding rain-gauge stations at north-east monsoon are shown in the supplementary Figure (S4-S6). From Figure S4 (g–l), it was observed that at the seasonal scale, i.e., during the north-east monsoon, the rainfall distributions between the gridded and station datasets were generally comparable, although noticeable station-wise differences were observed. The median rainfall for the gridded and station datasets was approximately 210 mm and 225 mm at Lakkavalli, 130 mm and 120 mm at Narsingpur, 107 mm and 113 mm at Gokak Falls, 113 mm and 105 mm at Mudhol, 113 mm and 98 mm at Bagalkot, and 138 mm and 142 mm at Haralahalli, respectively. The gridded dataset showed higher median rainfall at Narsingpur, Mudhol, and Bagalkot, whereas the station dataset exhibited slightly higher median values at Lakkavalli, Gokak Falls, and Haralahalli. Overall, Figure S4 indicates relatively good agreement between the gridded and station datasets in terms of central tendency, although differences in variability and extreme rainfall values were evident at individual stations.

From Figure S5 (m–r), it was observed that at the seasonal scale, i.e., during the north-east monsoon, the rainfall distributions varied considerably between the gridded and station datasets across the selected stations. The median rainfall for the gridded and station datasets was approximately 113 mm and 108 mm at Talikot, 145 mm and 100 mm at Madhira, 162 mm and 130 mm at Vijayawada, 125 mm and 145 mm at Byaladahalli, 112 mm and 70 mm at Daddi, and 82 mm and 97 mm at Sadalga, respectively. Overall, the gridded dataset exhibited higher median rainfall at Talikot, Madhira, Vijayawada, and Daddi, whereas the station dataset showed higher median rainfall at Byaladahalli and Sadalga. The figures also indicate differences in rainfall variability and extreme values between the two datasets, particularly at Madhira, Vijayawada, and Sadalga. Overall, Figure S5 demonstrates that the agreement between gridded and station NEV rainfall varies among stations, highlighting the importance of station-specific evaluation of gridded rainfall products during the south-west monsoon.

From Figure S6 (s–w), it was observed that at the seasonal scale, i.e., during the north-east monsoon, the rainfall distributions showed moderate differences between the gridded and station datasets across the selected stations. The median rainfall for the gridded and station datasets was approximately 125 mm and 140 mm at Haralahalli, 150 mm and 160 mm at Gandlapet, 155 mm and 125 mm at Keesara, 98 mm and 86 mm at Karad, and 113 mm and 113 mm at Gokak Falls, respectively. The gridded dataset exhibited higher median rainfall at Keesara and Karad, while the station dataset showed slightly higher median values at Haralahalli and Gandlapet, with nearly identical values at Gokak Falls. Differences in rainfall variability and extreme values were also evident, particularly at Haralahalli, Gandlapet, and Keesara, where several high-rainfall outliers were observed. Overall, Figure S6 indicates a relatively comparable central tendency between the gridded and station datasets, although station-specific differences in variability and extreme rainfall characteristics were evident.

Similarly, from Figure 6 (a-f), it was observed that at annual scale, the mean value for gridded datasets varied from 498.88 mm to 2050.31 mm, whereas for station datasets it varied from 487.52 mm to 1430.6 mm. The median value for gridded datasets varied from 487.71 mm to 1991.09 mm, whereas for station datasets it varied from 481.15 mm to 1392.2 mm. The maximum value for gridded datasets varied from 802.99 mm to 4390.51 mm, whereas for station datasets it varied from 793 mm to 3435 mm. The minimum value for gridded datasets varied from 153.53 mm to 819.52 mm, whereas for station datasets it varied from 156.3 mm to 862 mm. Thus, it can be stated that in case of annual scale, the reported gridded rainfall is significantly more than the corresponding station rainfall particularly in higher rainfall areas. Similar findings were observed by Chakraborty et al. (2018), where the gridded datasets had dissimilarities in variation when compared with station datasets across various locations and at seasonal and annual scale. The standard deviation value for gridded datasets varied from 135.1 mm to 887 mm, whereas for station datasets it varied from 143.02 mm to 697.85 mm.

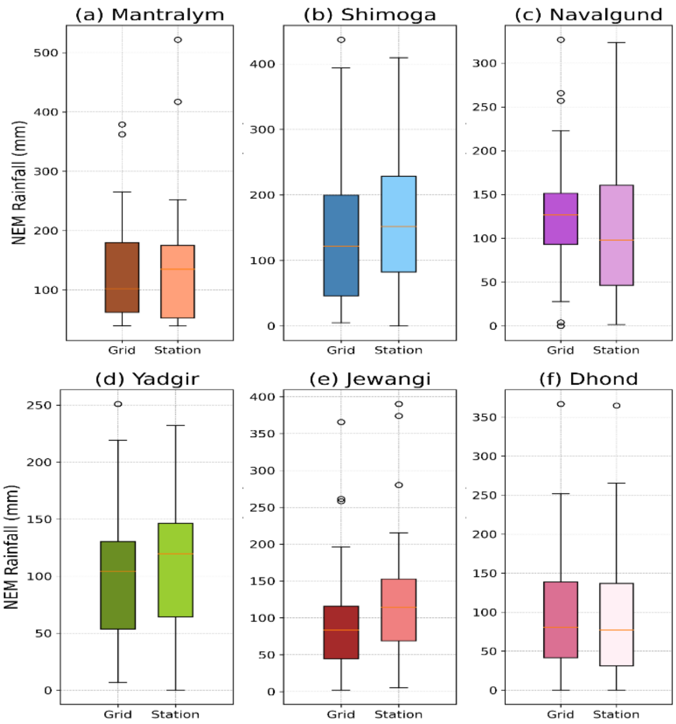

Figure 5 (a-f). Boxplot showing statistical parameters at north-east monsoon (NEM) for grid points and their corresponding rain-gauge stations at six locations

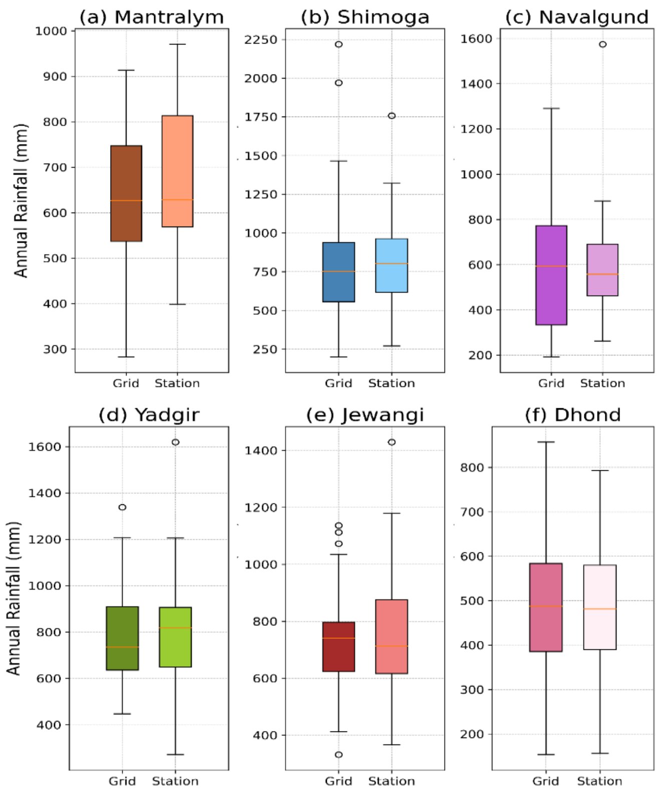

Figure 6 (a-f). Boxplot showing statistical parameters at annual scale for grid points and their corresponding rain-gauge stations at six locations

The coefficient of variation value for gridded datasets varied from 0.23 to 0.83, whereas for station datasets it varied from 0.18 to 0.49. Also, the skewness value for gridded datasets varied from -0.22 to 2.23, whereas for station datasets it varied from -0.06 to 2.27.

The boxplots for all the other grid points and their corresponding rain-gauge stations at annual scale are shown in the supplementary Figure (S7-S9). From Figure S7 (g–l), it was observed that at the annual scale, substantial station-wise differences exist between the gridded and station-based rainfall datasets. The median annual rainfall for the gridded and station datasets was approximately 2000 mm and 1300 mm at Lakkavalli, 660 mm and 1390 mm at Narsingpur, 720 mm and 485 mm at Gokak Falls, 570 mm and 500 mm at Mudhol, 565 mm and 485 mm at Bagalkot, and 605 mm and 710 mm at Haralahalli, respectively. The gridded dataset generally exhibited higher median rainfall at Lakkavalli, Gokak Falls, Mudhol, and Bagalkot, whereas the station dataset showed higher median rainfall at Narsingpur and Haralahalli. Considerable differences in rainfall variability and extreme values were also evident, particularly at Lakkavalli and Gokak Falls, where the gridded dataset showed several high-rainfall outliers. Overall, Figure S7 demonstrates that the agreement between gridded and station rainfall datasets varies considerably among stations, highlighting the importance of station-specific evaluation of gridded rainfall products at the annual scale.

From Figure S8 (m–r), it was observed that at the annual scale, considerable station-wise differences exist between the gridded and station-based rainfall datasets. The median annual rainfall for the gridded and station datasets was approximately 550 mm and 540 mm at Talikot, 1070 mm and 800 mm at Madhira, 950 mm and 855 mm at Vijayawada, 850 mm and 610 mm at Byaladahalli, 720 mm and 840 mm at Daddi, and 595 mm and 620 mm at Sadalga, respectively. The gridded dataset generally exhibited higher median rainfall at Madhira, Vijayawada, and Byaladahalli, whereas the station dataset showed higher median rainfall at Daddi and Sadalga, with relatively comparable values at Talikot. Considerable differences in rainfall variability and extreme values were also observed, particularly at Byaladahalli, where several high-rainfall outliers occurred in the gridded dataset. Overall, Figure S8 demonstrates that the agreement between gridded and station rainfall datasets varies considerably among stations, emphasizing the importance of station-specific evaluation of gridded rainfall products at the annual scale.

From Figure S9 (s–w), it was observed that at the annual scale, considerable differences exist between the gridded and station-based rainfall distributions across the selected stations. The median annual rainfall for the gridded and station datasets was approximately 620 mm and 710 mm at Haralahalli, 1010 mm and 630 mm at Gandlapet, 1110 mm and 840 mm at Keesara, 890 mm and 750 mm at Karad, and 570 mm and 480 mm at Gokak Falls, respectively. The gridded dataset generally exhibited higher median rainfall at Gandlapet, Keesara, Karad, and Gokak Falls, whereas the station dataset showed a higher median at Haralahalli. Considerable differences in rainfall variability and extreme values were also evident, particularly at Haralahalli, Gandlapet, and Keesara, where several high-rainfall outliers were observed. Overall, Figure S9 demonstrates that the agreement between gridded and station rainfall datasets varies considerably among stations, emphasizing the importance of station-specific evaluation of gridded rainfall products at the annual scale.

The time-series of SPI and SPEI were computed using gridded and station data at a 3-month time scale. The estimates of time series plots for both SPI and SPEI at 3-month time scale are shown in Figures 7 and 8 respectively. In Figures 7 (a-d) and 8 (a-d), the blue colour denotes the indices value of gridded data, the red colour represents the indices value of observed point data, and the thick black line indicates the drought threshold value of -1.

3.3 Drought monitoring

The drought characteristics such as the average drought duration, severity and the total drought months for all the grid points and their corresponding rain-gauge stations using SPI and SPEI at 3-month timescales was calculated using the run theory approach for the study period as shown in Figure 9 and 10 respectively. From Figure 9, it was observed that, at SPI-3 month timescale, the average drought duration (in months) for gridded datasets varied from 1.5 to 4, whereas for station datasets it varied from 2 to 5.

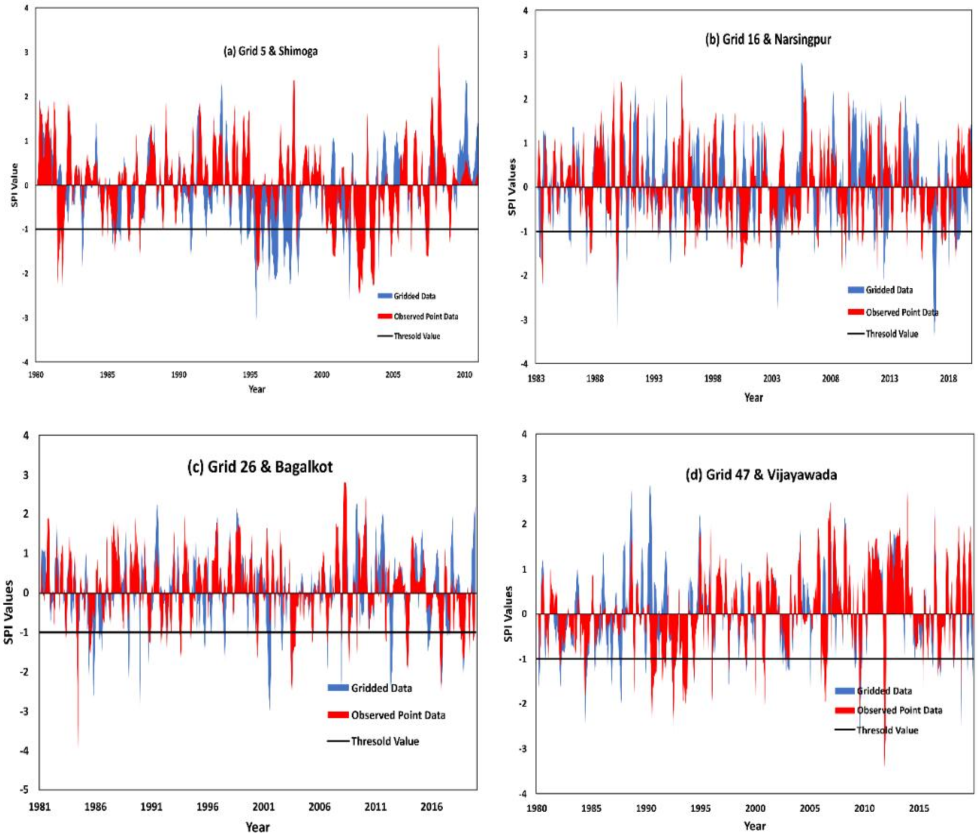

Figure 7 (a-d). Estimated timeseries plot of IMD grid points and rain-gauge stations using SPI at 3-month timescales

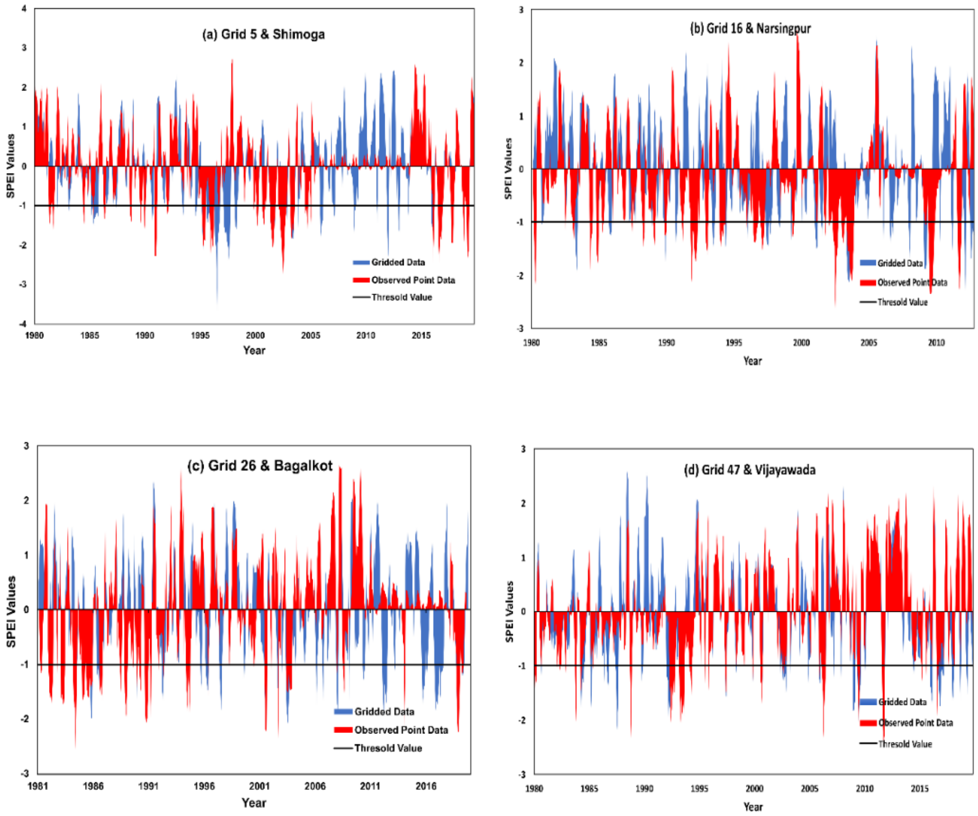

Figure 8 (a-d). Estimated timeseries plot of IMD grid points and rain-gauge stations using SPEI at 3-month timescales

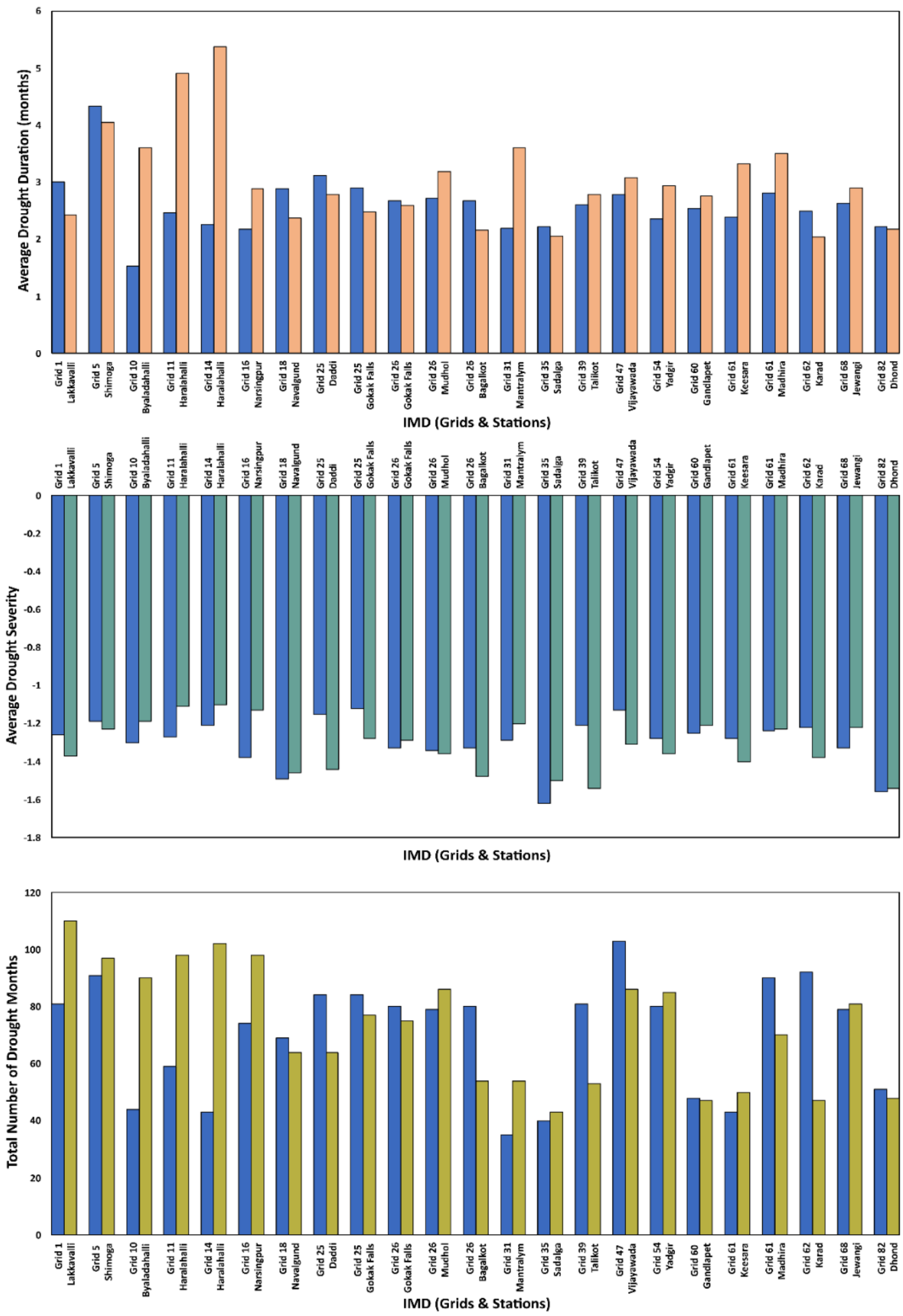

Figure 9. Drought Characteristics such as average drought duration, severity (in months) and the total number of drought months using SPI-3 at both gridded and station datasets.

The average drought severity for gridded datasets varied from -1.12 to -1.62 with maximum drought severity for an event ranging from -1.95 to -4.28, whereas the average drought severity for station datasets varied from -1.10 to -1.54 with maximum drought severity for an event ranging from -1.96 to -4.52. Also, the total number of drought months for gridded datasets varied from 35 to 103 whereas for station datasets it varied from 43 to 102. This indicates that the smaller number of drought duration, severity and total drought months are captured from gridded rainfall datasets when compared with station datasets.

Similarly, from Figure 10, it was observed that, at SPEI-3 month timescale, the average drought duration for gridded datasets varied from 2 to 4, whereas for station datasets it varied from 2 to 5. The average drought severity for gridded datasets varied from -1.17 to -1.35 with maximum drought severity for an event ranging from -2.09 to -4.04, whereas the average drought severity for station datasets varied from -1.08 to -1.42 with maximum drought severity for an event ranging from -1.93

to -3.48. Also, the total number of drought months for gridded datasets varied from 51 to 120 whereas for station datasets it varied from 55 to 141. This indicates that the smaller number of average drought duration, severity and total drought months are captured from gridded rainfall datasets when compared with station datasets.

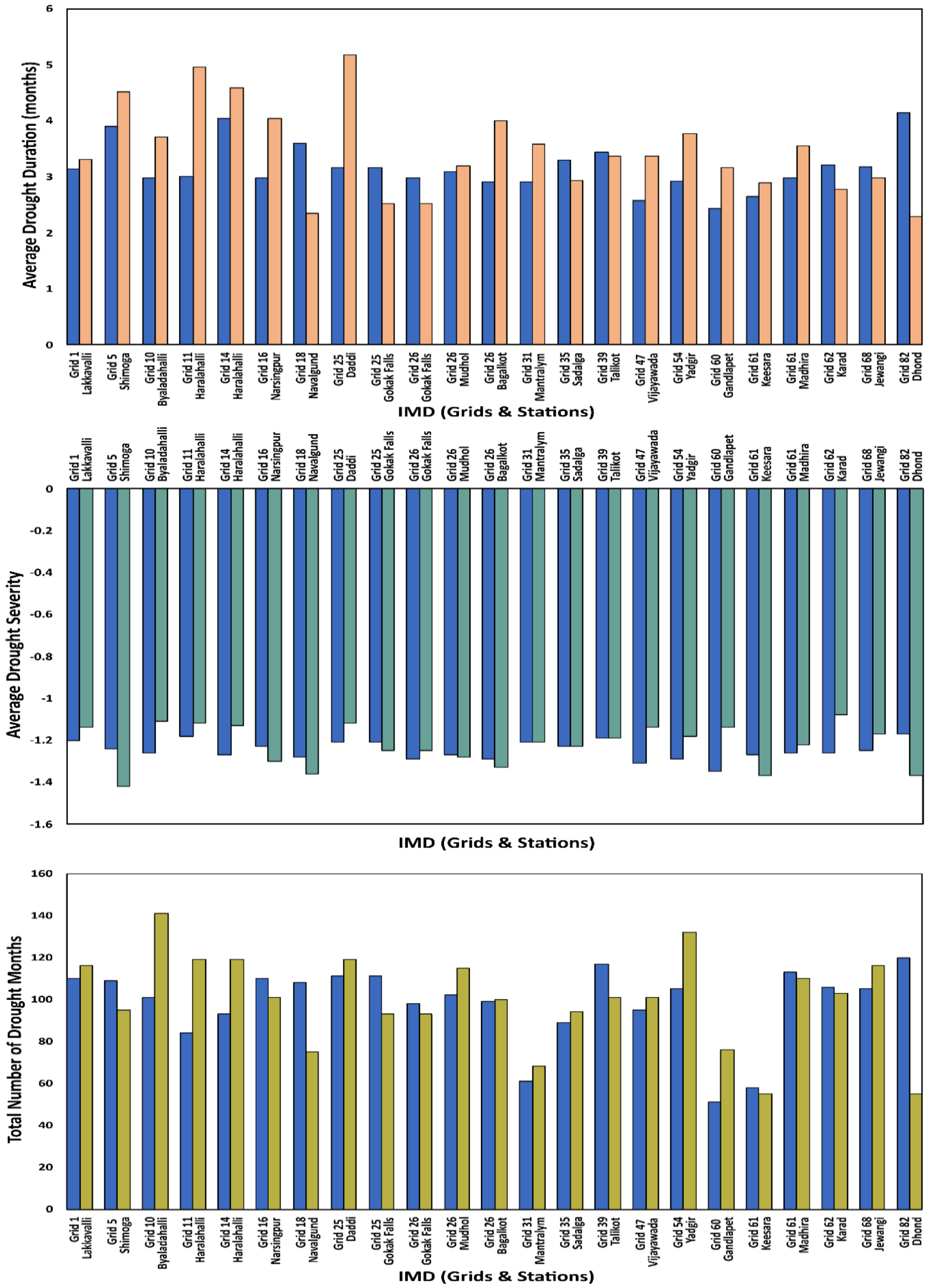

Figure 10. Drought Characteristics such as average drought duration, severity (in months) and the total number of drought months using SPEI-3 at both gridded and station datasets.

Also, the total drought months for all the grid points and their corresponding rain-gauge stations was calculated for both seasonal (south-west and north-east monsoon) and annual scale, and also the total number of moderate, severe, and extreme drought months was calculated using SPI-3 and SPEI-3 for the study period as shown in Figure 11 and 12 respectively.

For the drought estimation in any region, the number of stations and their distribution over the area is important as the observed station datasets are used in preparation of gridded datasets to mitigate bias. The density and quality of such data are important in order to reduce errors (Jafari et al., 2020). It is also important to note that the number of stations used in the gridded datasets located in any region will have a great influence too (Schumacher et al., 2020). Using SPI 3-month timescale, at seasonal scale i.e., for south-west monsoon, the total number of drought months for gridded datasets varied from 8 to 30, whereas for station datasets it varied from 13 to 32. At north-east monsoon, the total number of drought months for gridded datasets varied from 6 to 16, whereas for station datasets it varied from 4 to 17.

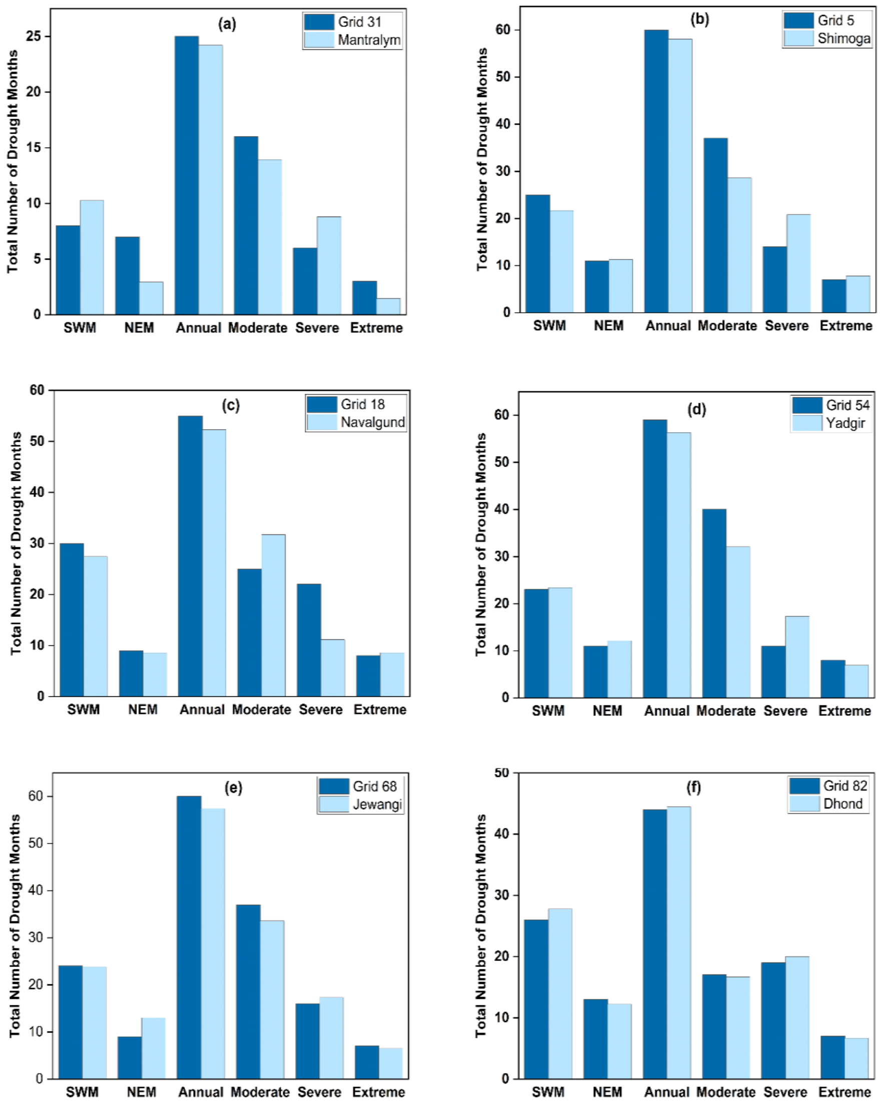

Figure 11 (a-f). Total number of drought months for grid points and their corresponding rain-gauge stations using SPI at 3-month timescale

At annual scale, the total number of drought months for gridded datasets varied from 25 to 71, whereas for station datasets it varied from 31 to 73. The total number of moderate drought months for gridded datasets varied from 16 to 51, whereas for station datasets it varied from 15 to 38. The total number of severe drought months for gridded datasets varied from 6 to 22, whereas for station datasets it varied from 7 to 24. The total number of extreme drought months for gridded datasets varied from 2 to 16, whereas for station datasets it varied from 2 to 12. Thus, it can be stated that the total number of drought months are captured less from gridded datasets at seasonal and annual scale, and also for severe droughts except for moderate and extreme drought categories, when compared with that of station datasets. The total drought months for all the other grid points and their corresponding rain-gauge stations are shown in the supplementary Figure (S10-S12). Figure S10 shows that at the annual scale, the total number of drought months for the gridded datasets varied from 28 to 60, whereas for the station datasets it varied from 29 to 60. The total number of moderate drought months for the gridded datasets varied from 21 to 37, compared with 16 to 38 for the station datasets. Similarly, the total number of severe drought months ranged from 6 to 14 for the gridded datasets and 6 to 16 for the station datasets. For extreme droughts, the corresponding ranges were 1–14 months for the gridded datasets and 2–10 months for the station datasets. Overall, the gridded and station datasets exhibited broadly comparable drought frequencies at the annual scale, although noticeable station-specific differences were observed, particularly for moderate and severe drought categories. The results indicate that the gridded dataset generally captures fewer drought months for seasonal and annual drought conditions and severe droughts at several stations, whereas extreme drought occurrence shows relatively mixed differences between the two datasets. Figure S11 shows that at the annual scale, the total number of drought months for the gridded datasets varied from 36 to 71, whereas for the station datasets it varied from 36 to 73. The total number of moderate drought months for the gridded datasets varied from 24 to 51, compared with 18 to 43 for the station datasets. The total number of severe drought months ranged from 5 to 13 for the gridded datasets and 15 to 25 for the station datasets. For extreme droughts, the corresponding ranges were 3–7 months for the gridded datasets and 0–14 months for the station datasets. Overall, the gridded and station datasets show comparable total drought frequencies at the annual scale, although considerable station-specific differences are evident for individual drought severity categories. In particular, the gridded dataset generally captures fewer severe drought months than the station observations, while differences in extreme drought occurrence are more variable across the stations.

Figure S12 shows that at the annual scale, the total number of drought months for the gridded datasets varied from 29 to 69, whereas for the station datasets it varied from 29 to 68. The total number of moderate drought months for the gridded datasets varied from 19 to 50, compared with 16 to 45 for the station datasets. Similarly, the total number of severe drought months ranged from 9 to 12 for the gridded datasets and 6 to 14 for the station datasets. For extreme droughts, the corresponding ranges were 0–14 months for the gridded datasets and 3–12 months for the station datasets. Overall, the gridded and station datasets show broadly comparable total drought frequencies at the annual scale, although notable station-specific differences are observed across the drought severity categories. The gridded dataset generally captures fewer moderate and severe drought months than the station observations at several locations, while the differences in extreme drought occurrence are more variable between the two datasets.

Similarly, using SPEI-3 month timescale, at seasonal scale i.e., for south-west monsoon, the total number of drought months for gridded datasets varied from 15 to 32, whereas for station datasets it varied from 14 to 32. At north-east monsoon, the total number of drought months for gridded datasets varied from 4 to 16, whereas for station datasets it gave the same count as in gridded datasets i.e., 4 to 16. At annual scale, the total number of drought months for gridded datasets varied from 48 to 84, whereas for station datasets it varied from 34 to 105. The total number of moderate drought months for gridded datasets varied from 33 to 59, whereas for station datasets it varied from 22 to 79. The total number of severe drought months for gridded datasets varied from 10 to 27, whereas for station datasets it varied from 9 to 31. The total number of extreme drought months for gridded datasets varied from 1 to 10, whereas for station datasets it varied from 1 to 14. Thus, it can be stated that the total number of drought months captured at seasonal scale both at south-west monsoon and north-east monsoon are almost same, whereas the total number of drought months captured at annual scale, and also for moderate, severe and extreme drought categories are less from gridded datasets when compared with that of station datasets. The total number of drought months for all the other grid points and their corresponding rain-gauge stations are shown in the supplementary Figure (S13-S15).

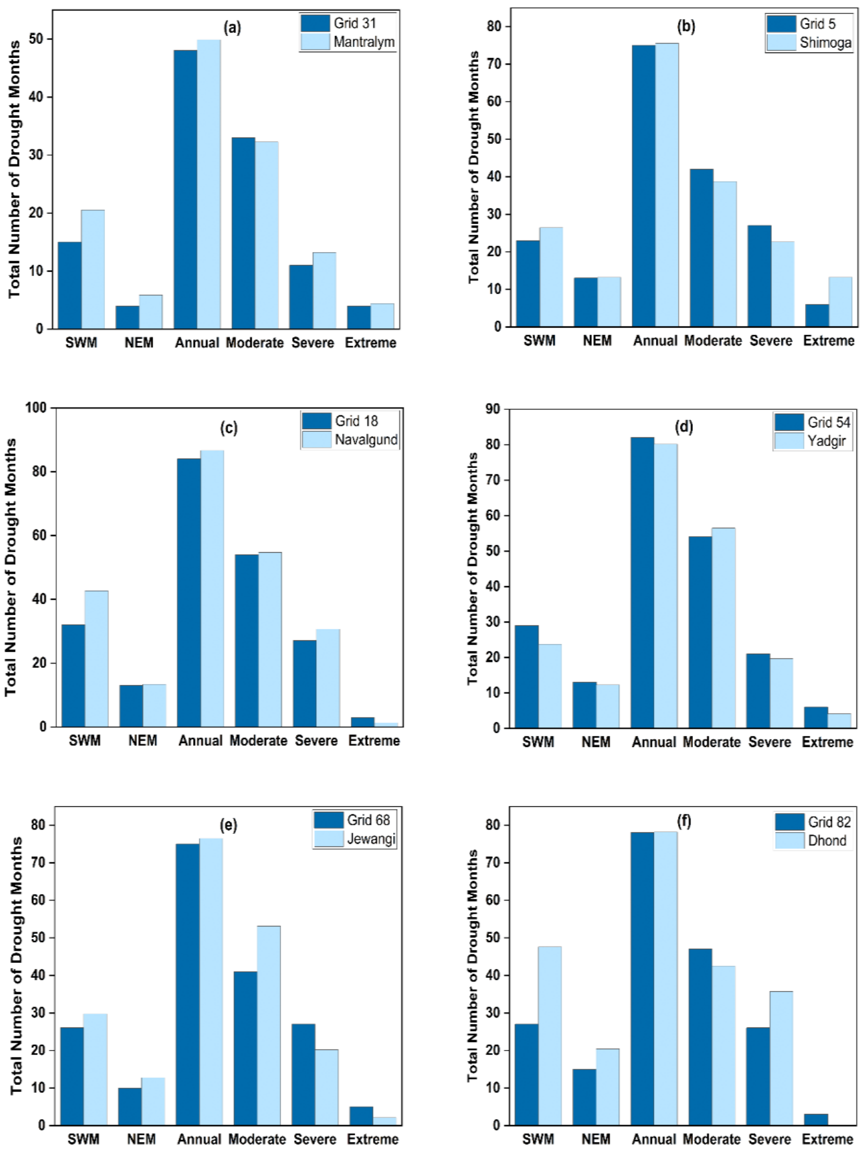

Figure 12 (a-f). Total number of drought months for grid points and their corresponding rain-gauge stations using SPEI at 3-month timescale.

Figure S13 shows that at the annual scale, the total number of drought months for the gridded datasets varied from 63 to 80, whereas for the station datasets it varied from 61 to 81. The total number of moderate drought months for the gridded datasets varied from 47 to 56, compared with 37 to 59 for the station datasets. Similarly, the total number of severe drought months ranged from 10 to 26 for the gridded datasets and 12 to 31 for the station datasets. For extreme droughts, the corresponding ranges were 1–6 months for the gridded datasets and 3–11 months for the station datasets. Overall, the gridded and station datasets show broadly comparable annual drought frequencies; however, notable differences are evident in the distribution of drought severity categories. The gridded dataset generally indicates fewer moderate, severe, and extreme drought months than the station observations at several locations, highlighting station-specific differences in drought characterization.Figure S14 shows that at the annual scale, the total number of drought months for the gridded datasets varied from 73 to 83, whereas for the station datasets it varied from 74 to 82. The total number of moderate drought months for the gridded datasets varied from 46 to 59, compared with 50 to 56 for the station datasets. Similarly, the total number of severe drought months ranged from 14 to 24 for the gridded datasets and 15 to 21 for the station datasets. For extreme droughts, the corresponding ranges were 3–6 months for the gridded datasets and 0–9 months for the station datasets. Overall, the gridded and station datasets show broadly comparable total drought frequencies at the annual scale, although noticeable station-specific differences are evident across the drought severity categories. The gridded dataset generally captures fewer moderate and extreme drought months at several stations, while differences in severe drought occurrence are relatively small.

Figure S15 compares the number of drought events identified from gridded and station datasets across different drought categories. At the annual scale, the total number of drought events for gridded datasets varied from 48 to 80, whereas for station datasets it ranged from 50 to 82. For moderate droughts, the corresponding ranges were 33–51 and 32–54, respectively. For severe droughts, gridded datasets recorded 11–24 events, compared with 12–20 events from station datasets. For extreme droughts, the ranges were 2–10 and 4–7 events for gridded and station datasets, respectively. Overall, the gridded and station datasets show broadly comparable drought-event frequencies, with noticeable differences at individual locations and drought severity levels. The agreement is generally stronger for annual and moderate droughts, while greater discrepancies are observed for severe and extreme drought events.

4. CONCLUSIONS

Good quality datasets at any locations are the initial step towards the estimation and mitigation of drought events at regional or global scale. The manually observatory or station datasets are not easily accessible in many regions including short length and many gaps in data records, and for this reason the gridded datasets are usually used in the drought studies. However, the gridded datasets too have some limitations as they are prepared from interpolation technique. Also, in some regions the station data are accessible, but drought studies have not been done. Hence, it is essential to check the reliability of gridded and station datasets for the meteorological drought estimation and its characteristics which will help decision makers in areas of environmental science. In the present study, a comparative analysis of precipitation and temperature datasets (maximum and minimum) were analysed for the meteorological drought estimation between gridded and station datasets of IMD in the Krishna River Basin of India for the study period 1980-2019. The meteorological drought indices used for the drought estimation are the SPI and SPEI at 3-month timescales. The drought characteristics such as average drought duration, severity, and the total drought months were obtained using the run theory approach. Further to better understand the reliability of both the datasets, a detailed comparison on the statistical parameters like coefficient of determination, coefficient of variation, mean, median, maximum, and minimum value, standard deviation, skewness, and the total number of drought months were checked at seasonal (south-west and north-east monsoon) and annual scale. Thus, from the above analysis, the following conclusion can be drawn:

In case of south-west monsoon (SWM), the gridded rainfall dataset shows notably higher rainfall compared to the observed station rainfall at corresponding rain gauge station. There is no significant difference observed in case of north-east monsoon (NEM), between the gridded rainfall dataset and observed station rainfall at corresponding rain gauge station. Whereas, in case of annual scale, the reported gridded rainfall is significantly more than the corresponding station rainfall particularly in higher rainfall areas.

The drought characteristics obtained using SPI and SPEI at 3-month timescale, indicates that less number of average drought duration, severity and total drought months are captured from gridded rainfall datasets when compared with station datasets. Using SPI at 3-month timescale, the total number of drought months captured were less from gridded datasets at annual and seasonal scale, and for severe drought category, except for moderate and extreme drought categories, when compared with that of station datasets. Whereas, using SPEI at 3-month timescale, the total number of drought months captured were almost same from gridded datasets at annual and seasonal scale, and for severe drought category when compared with that of station datasets. The total number of drought months captured were less for moderate and extreme drought categories, when compared with that of station datasets.

Thus, the analysis results show that the IMD gridded datasets could not capture all of the moderate, severe, and extreme drought months accurately during the study period. This might be because the IMD gridded datasets have been estimated using interpolation of observed rainfall in the stations in the vicinity of the given grid. On the other hand, the IMD station datasets captured most of the moderate, severe, and extreme drought months more accurately. Thus, it is essential to note that the IMD station datasets give a more realistic assessment of drought events. Therefore, the IMD station datasets should be preferred over IMD gridded ones for better accuracy of drought forecasting and early warning systems.

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