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Dry spell characteristics over India based on IMD and APHRODITE datasets

L. Sushama · S. Ben Said · M. N. Khaliq · D. Nagesh Kumar · R. Laprise

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Abstract Selected characteristics of dry spells and associated trends over India during the 1951–2007 period is studied using two gridded datasets: the Indian Meteorological Department (IMD) and the Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation of the water resources (APHRODITE) datasets. Two precipitation thresholds, 1 and 3 mm, are used to define a dry day (and therefore dry spells) in this study. Comparison of the spatial patterns of the dry spell characteristics (mean number of dry days, mean number of dry spells, mean and maximum duration of dry spells) for the annual and summer monsoon period obtained with both datasets agree overall, except for the northernmost part of India. The number of dry days obtained with APHRODITE is larger for this region compared to IMD, which is consistent with the smaller precipitation for the region in APHRODITE. These differences are also visible in the spatial patterns of mean and maximum dry spell durations. Analysis of field significance associated with trends, at the level of 34 predefined meteorological subdivisions over the mainland, suggests better agreement between the two datasets in positive trends associated with number of dry days for the annual and summer monsoon period, for both thresholds. Important differences between the two datasets are noted in the field significance associated with the negative trends. While negative trends in annual maximum duration of dry spells appear field significant for the desert regions according to both datasets, they are found field significant for two regions (Punjab and South Interior Karnataka) for the monsoon period for both datasets. This study, in addition to providing information on the spatial and temporal patterns associated with dry spell characteristics, also allows identification of regions and characteristics where the two datasets agree/disagree.

Keywords Dry spells · Gridded precipitation data · India · Trends

L. Sushama (✉) · S. Ben Said · M. N. Khaliq · R. Laprise
Centre ESCER, University of Quebec at Montreal, 201 Président-Kennedy, Montreal, QC H2X 3Y7, Canada
e-mail: sushama.laxmi@uqam.ca

M. N. Khaliq
Global Institute for Water Security and School of Environment and Sustainability, University of Saskatchewan, Saskatoon, SK, Canada

D. Nagesh Kumar
Department of Civil Engineering, Indian Institute of Science, Bangalore, India

1 Introduction

Agriculture plays a very important role in Indian economy, with over 70 % of the population depending on revenue from agriculture. Variations in precipitation patterns, and therefore variations in the frequency of droughts and floods can have negative effects on agricultural food production. The southwest summer monsoon, occurring from June through September, is the most important rainy season for the country, and provides rain required for two main crop growing seasons: Kharif (summer) and Rabi (winter) (Revadekar and Preethi 2011). While heavy precipitation events during critical phase of crop growth can affect food grains (Revadekar and Preethi 2011), small water deficiencies may put heavy drought stress on agriculture (Gong et al. 2004). Therefore, study of both floods and droughts and their associated characteristics are important for better management of water resources, particularly in the context of a changing climate, to assist proper planning and adaptation strategies. The primary tools used to study anticipated climate change are the Coupled Global Climate Models (CGCMs) and Regional Climate Models (RCMs) and the transient climate-change simulations obtained when those models are run with projected anthropogenic forcing. An important preliminary step before looking at projected changes based on climate models is the evaluation of these models, by comparing simulated characteristics of variables of interest to those observed or to those derived from various data products at appropriate spatial resolutions. It is very plausible that two different observed/reanalyzed datasets can have significant differences for some characteristics and regions, depending on the type and quality of the underlying data considered in developing gridded datasets, interpolation technique used, etc.

The aim of this study is twofold. The first aim is to further enhance the assessment of the evolution of dry spell characteristics over India during the 1951–2007 period using two gridded datasets, the Indian Meteorological Department (IMD) (Rajeevan et al. 2006) and Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation of the water resources (APHRODITE) (Yatagai et al. 2009) datasets. The second aim is to identify important differences (if any) in the dry spell characteristics derived from the two datasets. Due to an increasing tendency of climate change related studies over the region, this information would be useful to those interested in the verification of climate model simulated dry spell characteristics, as well as to those related to agriculture and water management activities. For example, Uma et al. (2013) recently documented differences in the large-scale features, including intra-seasonal oscillations of southwest monsoon rainfall, in IMD dataset and Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA).

Dry spell in this article is defined as an extended period of dry days (e.g. Tebaldi et al. 2006; Sushama et al. 2010), where a dry day is a day with precipitation less than a preselected threshold. Though a number of studies have looked at trends in southwest monsoon rainfall (Subbaramayya and Naidu 1992; Guhathakurta and Rajeevan 2008) and extreme rain events over India (Ray and Srivastava 2000; Goswami et al. 2006; Joshi and Rajeevan 2006; Rajeevan et al. 2008; Ghosh et al. 2009), dry spell characteristics and their trends have received much less attention.

Recently, Singh and Ranade (2010) studied wet and dry spells for 19 subregions of India, for the 1951–2007 period, using the IMD data. A dry (wet) spell, in their study, is defined as a continuous period with daily precipitation less (equal to or greater) than the climatological daily mean precipitation for the summer monsoon period. It must be noted here that the 19 subregions considered in their study were defined based on physio-climatological factors, and the threshold used to identify wet/dry spells varies from region to region. Thus a relative threshold, i.e. threshold based on local precipitation climatology, is used. The choice of a relative versus absolute threshold depends on the purpose of the study. The criterion used in this study is constant in space, and is considered sufficient in the analysis of dry spells considered here. The active and break periods during the southwest monsoon season were studied by Rajeevan et al. (2006), based on the same IMD dataset, using an objective criterion based on standardized daily precipitation anomaly for defining spells. Their results suggested no significant trend in the number of break and active days during the southwest monsoon season for the 1951–2003 period.

This study differs from the previous studies in the use of two different gridded datasets and in the precipitation thresholds used to define dry days and therefore dry spells, and advances current understanding of dry spells over India through a systematic analysis of various dry spell characteristics. The characteristics considered in this study are, mean number of dry days and dry spells, mean duration of dry spells, maximum duration of dry spells and trends in number of dry days and maximum duration of dry spells, for the annual and southwest summer monsoon (i.e. June–September) periods. Statistical significance of trends is assessed both at grid cell and regional level, where regions here correspond to pre-defined subdivisions, shown in Fig. 1. India has been divided into 36 subdivisions by IMD based on meteorological considerations, of which 34 are on mainland and two on islands. In this study we consider only the 34 mainland subdivisions (Fig. 1).

The paper is organized as follows. Data and methods used are presented in Sect. 2. Analysis of dry spell characteristics based on IMD and APHRODITE datasets are presented in Sect. 3, followed by summary and conclusions in Sect. 4.

2 Data and methods

2.1 Data

As mentioned earlier, two different datasets are considered in the present study—the third version of the IMD $1^\circ \times 1^\circ$ daily gridded precipitation data (Rajeevan et al. 2006) and the $0.5^\circ \times 0.5^\circ$ APHRODITE gridded daily precipitation data for Monsoon Asia, developed by the Research Institute for Humanity and Nature (RIHN) and the Meteorological Research Institute of Japan Meteorological Agency (MRI/JMA). The IMD data is arranged in 35×33 grid points over India, following the interpolation method proposed by Shepard (1968) by considering 1,803 stations that have at least

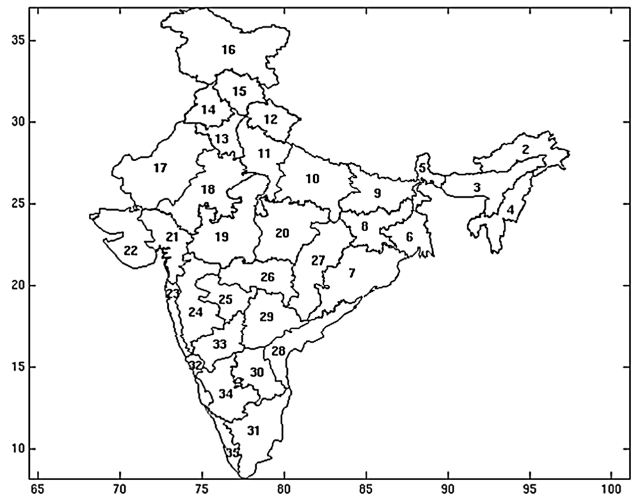


Fig. 1 Meteorological subdivisions of India (*2* Arunachal Pradesh; *3* Assam and Meghalaya; *4* Nagaland, Manipur, Mizoram and Tripura; *5* Sub-Himalayan West Bengal and Sikkim; *6* Gangetic West Bengal; *7* Orissa; *8* Jharkhand; *9* Bihar; *10* East Uttar Pradesh; *11* West Uttar Pradesh Plains; *12* West Uttar Pradesh Hills; *13* Haryana; *14* Punjab; *15* Himachal Pradesh; *16* Jammu and Kashmir; *17* West Rajasthan; *18* East Rajasthan; *19* West Madhya Pradesh; *20* East Madhya Pradesh; *21* Gujarat; *22* Saurashtra, Kutch and Diu; *23* Konkan and Goa; *24* Madhya Maharashtra; *25* Marathwada; *26* Vidarbha; *27* Chattisgarh; *28* Coastal Andhra Pradesh; *29* Telangana; *30* Rayalaseema; *31* Tamil Nadu and Pondicherry; *32* Coastal Karnataka; *33* North Interior Karnataka; *34* South interior Karnataka; *35* Kerala)

90 % data availability over the period considered. Though a higher resolution (0.5° × 0.5°) gridded dataset developed by IMD is available, it is not considered here following the discussion in Rajeevan and Bhate (2009) related to the possible temporal inhomogeneity in this data, which is not desirable, especially in the analysis of trends. For the APHRODITE dataset, the last version is considered, which includes more rain-gauge data, spans the required period and has better quality control when compared with previous version (Yatagai et al. 2009). For more details on data sources used in developing APHRODITE, readers are referred to Yatagai et al. (2009). The APHRODITE Monsoon Asia data is available over a domain of 180 × 140 grid points covering the 60°E–150°E, 15°S–55°N region. The interpolation algorithm for the new version of APHRODITE is similar to that presented by Yatagai et al. (2009) with improvements in weighting function to consider the local topography between the rain-gauge and the interpolated point.

2.2 Methods

The dry spell characteristics considered are the mean number of dry days, mean number of dry spells, and mean and maximum duration of dry spells, for both annual and southwest summer monsoon (JJAS) cases, for the 1951–2007 period. A dry spell is identified as an extended period of dry days (Suppiah and Hennessy 1998; Lana et al. 2006; Serra et al. 2006; Tebaldi et al. 2006; Beniston et al. 2007; May 2008; Sushama et al. 2010; Bouagila and Sushama 2013), where a dry day is a day with amount of precipitation less than a pre-defined threshold. In this study 1 and 3 mm thresholds are chosen and a spell length of at least 1 day is considered. The spatial patterns of the above characteristics derived from both datasets are compared to identify regions and characteristics where they agree/disagree. It must be noted that for the two datasets IMD and APHRODITE, all analyses are performed on respective grids, without any re-gridding. A total of 357 (1141) grid cells at 1° (0.5°) resolution cover the Indian landmass in the case of IMD (APHRODITE).

In this study, trend analysis is performed at two levels for mean number of dry days and maximum duration of dry spells. Firstly, trends and their significance are assessed at grid-cell level, following which the field significance of both positive and negative trends are assessed at regional scale, i.e. for the 34 pre-defined subdivisions shown in Fig. 1. Detailed description follows.

2.2.1 *Grid-cell level analysis*

The nonparametric Mann–Kendall (MK) test (Mann 1945; Kendall 1975) is used to evaluate the trend in dry spell characteristics at the respective resolutions of the two datasets. The MK test is based on the test statistic S that is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{1}$$

where n is the sample size, x_i and x_j are the sequential data values and

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if} \quad \theta > 0 \\ 0 & \text{if} \quad \theta = 0 \\ -1 & \text{if} \quad \theta < 0 \end{cases} \tag{2}$$

A positive (negative) value of S indicates an increasing (decreasing) trend but it does not specify whether the trend is linear or non-linear. For assessing statistical significance of trend, the mean and variance of S are computed as follows:

$$E[S] = 0 \tag{3}$$

and

$$\operatorname{Var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{g} t_i(t_i - 1)(2t_i + 5)\right] \tag{4}$$

where g is the number of tied groups (a tied group is a set of sample data having the same value), and t_i is the number of data points in the ith group. A test based on the normalapproximation can be formulated for samples with more than 8 values by calculating the standardized test statistic Z as follows (Mann 1945; Kendall 1975):

$$Z = \begin{cases} (S-1)/\sqrt{\mathrm{Var(S)}} & S > 0 \\ 0 & S = 0 \\ (S+1)/\sqrt{\mathrm{Var(S)}} & S < 0 \end{cases} \quad (5)$$

The probability associated with the test statistic Z is calculated as $P(Z) = 2[1 - \Phi(|Z|)]$, where Φ is the cumulative distribution function of the normal distribution. At a desired significance level α, the null hypothesis of no trend is rejected if $P(Z) \leq \alpha$.

The MK test assumes the time series values to be independent and identically distributed. If for a given time series this assumption is not fulfilled, then the evaluation of trend significance is severely impacted. In fact, if the time series values are positively (negatively) correlated then the MK test will suggest a significant trend more (less) often than it will for an independent series (Kulkarni and von Storch 1995; Khaliq et al. 2009a). To address this problem, various approaches have been suggested, e.g. pre-whitening (Kulkarni and von Storch 1995), modified pre-whitening (Wang and Swail 2001), block-bootstrap (e.g. Khaliq et al. 2009a), and variance-correction (e.g. Hamed and Rao 1998). In this work, we used the modified pre-whitening approach described in Wang and Swail (2001) to address the influence of only first-order serial correlation on trend significance. The influence of long-term persistence on trend significance documented in Cohn and Lins (2005) and Khaliq et al. (2009b) is not investigated.

2.2.2 *Regional level analysis*

When a number of individual tests of significance are performed for a meteorological or hydrological variable over a spatial domain of interest, it is important to evaluate the field significance of these tests. In the context of trends, the purpose of performing field significance analysis is to assess if the number of grid cells identified with significant trends may not have arisen due to coincidence and/or due to spatial structure of the variable. A number of techniques exist to evaluate field significance, e.g. using the theory of binomial distribution and Monte Carlo simulation procedure (Livezey and Chen 1983; Elmore et al. 2006), vector block bootstrap resampling approach (Yue et al. 2003; Khaliq et al. 2009a), and False Discovery Rate (FDR) approach (Wilks 2006). All of these techniques have their relative advantages/disadvantages. In the absence of a perfect approach, in the present work, the binomial distribution based approach presented in Livezey and Chen (1983) and the more recently proposed FDR approach (Wilks 2006) are used to evaluate field significance of trends at the regional level (Fig. 1).

According to the binomial distribution approach, overall field significance of trends at α_F level for a given region is assessed by comparing the number of grid-cell level significant trends M (say at α_L level) for the region, with the threshold number of significant trends M_0 (computed following Livezey and Chen (1983) and assuming $\alpha_F = 5\ \%$ and negligible spatial dependence) that must be equalled or exceeded to declare field significance. In other words, if $M \geq M_0$ for the region, then the results of trend analysis are assumed to be field significant at α_F level.

The FDR test is a relatively new approach of field significance analysis and it is also found to be robust to spatial dependence by Ventura et al. (2004) and Wilks (2006). This approach works with any statistical test for which one can generate a p value that is generally defined as the probability at which a test under consideration is statistically significant. Thus, as long as the effects of serial structure of time series is taken care of appropriately for evaluating grid-cell-level p values in a spatial domain of interest, the FDR test could be applied for field significance analysis. Let $p_{(i)}$ denote the ith smallest of K p values. The number of false trend detections can be controlled at the rate q by rejecting those tests for which $p_{(i)}$ is no greater than p_{FDR}, where

$$p_{FDR} = \max\left[p_{(i)} : p_{(i)} \leq q\ (i/K)\right], \quad \text{where } i = 1, \ldots, K. \quad (6)$$

If none of the grid-cell level p values satisfy the right-hand side of the above equation, then no field significance is declared. For performing field significance analysis using the FDR approach, q is assumed to be equal to 5 % in order to be consistent with the binomial distribution based approach.

As positive or negative temporal trends could be present in a region under consideration, field significance analysis is performed separately for negative and positive trends over 34 meteorological subdivisions of India, for both binomial and FDR approaches. This is consistent with the recommendations available in the published literature (e.g. Yue et al. 2003; Khaliq et al. 2009a) and would help identify regions with increasing or decreasing trends in characteristics of dry spells. No field significance is assessed for regions having only a single grid-cell with either positive or negative trend.

3 Results and discussion

3.1 Dry spell characteristics

Prior to analysing dry spell characteristics, it is useful to discuss the spatial patterns of mean annual and mean summer monsoon (i.e., JJAS) precipitation and their interannual variability (Fig. 2). The mean annual precipitation patterns over India show large spatial variability,

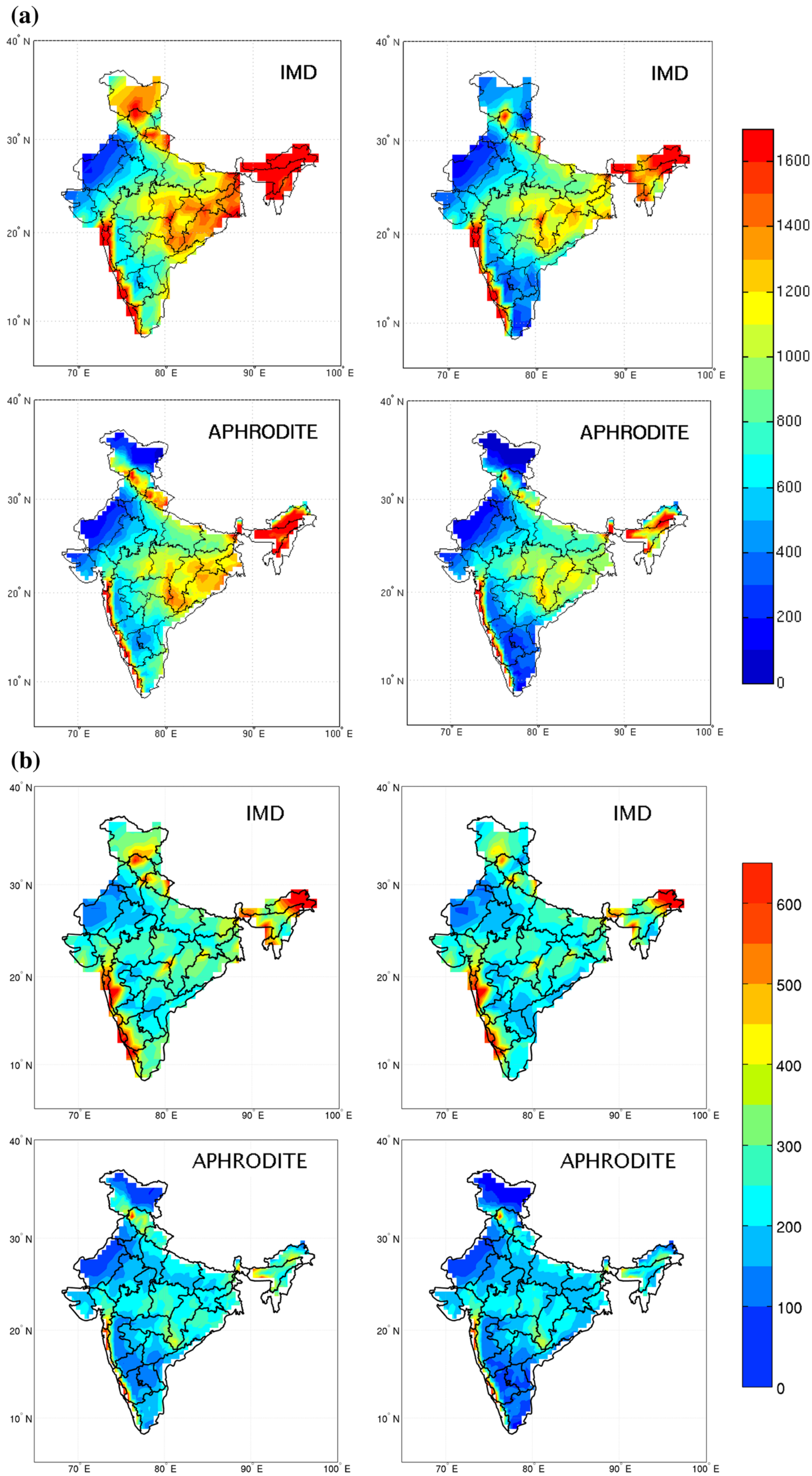


Fig. 2 **a** Mean annual (*left panels*) and mean summer monsoonal (*right panels*) precipitation based on IMD (1° × 1°) (*top panels*) and APHRODITE (*bottom panels*) datasets for the 1951–2007 period, and **b** their interannual variability. The unit is mm

with the west coast and the northeast parts of India receiving maximum amount of precipitation, while the northwest part of India get minimum precipitation (Fig. 2a). The comparison between mean annual precipitation and mean summer monsoon precipitation for the 1951–2007 period, for both IMD and APHRODITE data, shows that the bulk of annual precipitation falls during the summer monsoon period (June–September). It must be noted that though the northernmost part of India is deprived of the southwest monsoon, it receives precipitation from western disturbances. Though the general patterns are similar for both datasets, differences can be noted for the northern most part of India (Jammu and Kashmir), for both mean annual and summer monsoonal precipitation. Rajeevan and Bhate (2009) also obtained poor correlation coefficients for this region, for the 0.5° × 0.5° IMD and APHRODITE derived monsoon seasonal precipitation for the 1980–2002 period. Some differences can also be noted between IMD and APHRODITE data for some of the eastern regions, with IMD suggesting higher values compared to APHRODITE. The interannual variability in the annual and summer monsoonal precipitation in IMD is maximum along the west coast of peninsular India and the northeastern most regions of India (Fig. 2b), that receive maximum precipitation. The interannual variability in APHRODITE data is generally smaller compared to that in the IMD dataset.

Spatial distribution of the annual/monsoonal mean number of dry days for IMD and APHRODITE data for the 1951–2007 period for 1 and 3 mm precipitation thresholds are presented in Fig. 3. The patterns of mean number of dry days (Fig. 3) follow the inverse of the precipitation patterns (Fig. 2). For the mean annual number of dry days, minimum number of dry days is situated along the west coast and the northeast parts of India, and maximum number of dry days over the northwest part of India (Fig. 3). As expected, an increase in the mean number of dry days with increasing thresholds (from 1 to 3 mm) can be noted in Fig. 3. The spatial patterns of mean annual number of dry days for IMD and APHRODITE datasets are more similar for the higher 3 mm threshold, except for the northernmost part of India (Jammu and Kashmir). Consistent with the spatial distribution of annual precipitation shown in Fig. 2, more number of dry days is obtained for this northernmost region of India with APHRODITE compared with IMD dataset. The spatial patterns of mean number of dry days for the summer monsoon period (Fig. 3b) show minimum number of dry days along the northwest and southeast parts of India. The differences between the two datasets for the northernmost part are still clearly visible.

The spatial distribution of the mean annual and summer monsoonal number of dry spells is shown in Fig. 4. For the annual case, regions with more rainy days such as the southwest and northeast regions have larger number of short dry spells, while the northwest region has smaller number of dry spells (of longer durations), according to the definition of dry spell used in this study. Again the patterns are different for the northernmost part of India for the two datasets. The patterns are very similar for 1 and 3 mm thresholds except for the fact the number of dry spells for 3 mm is less than that for the 1 mm case, as is expected.

Figure 5 shows 57-year (1951–2007) mean annual and summer monsoonal duration of dry spells for IMD and APHRODITE data for 1 mm and 3 mm thresholds. The general patterns for IMD and APHRODITE data are similar, with larger values of mean duration of dry spells over the northwest part of India, characterized by an arid climate. The difference in mean duration of dry spell between IMD and APHRODITE data, especially in North India, is mainly due to the differences in precipitation datasets over the same area (Fig. 2). In this region, the mean duration of dry spells is larger in APHRODITE data than, with respect to IMD data, due to fewer rainy days as per the criterion used to define a dry spell. The comparison between Fig. 5a, b shows, as expected, that the mean duration of dry spell is less in monsoon period than the annual period. The east–west contrast in the mean duration of dry spells over the peninsula is very clear, especially at 3 mm threshold. During monsoons the duration of the dry spells for the southeast part of India is similar in magnitude to that for the dry northwest part. Minimum duration of 1–2 days is mostly seen for the northeast part of India.

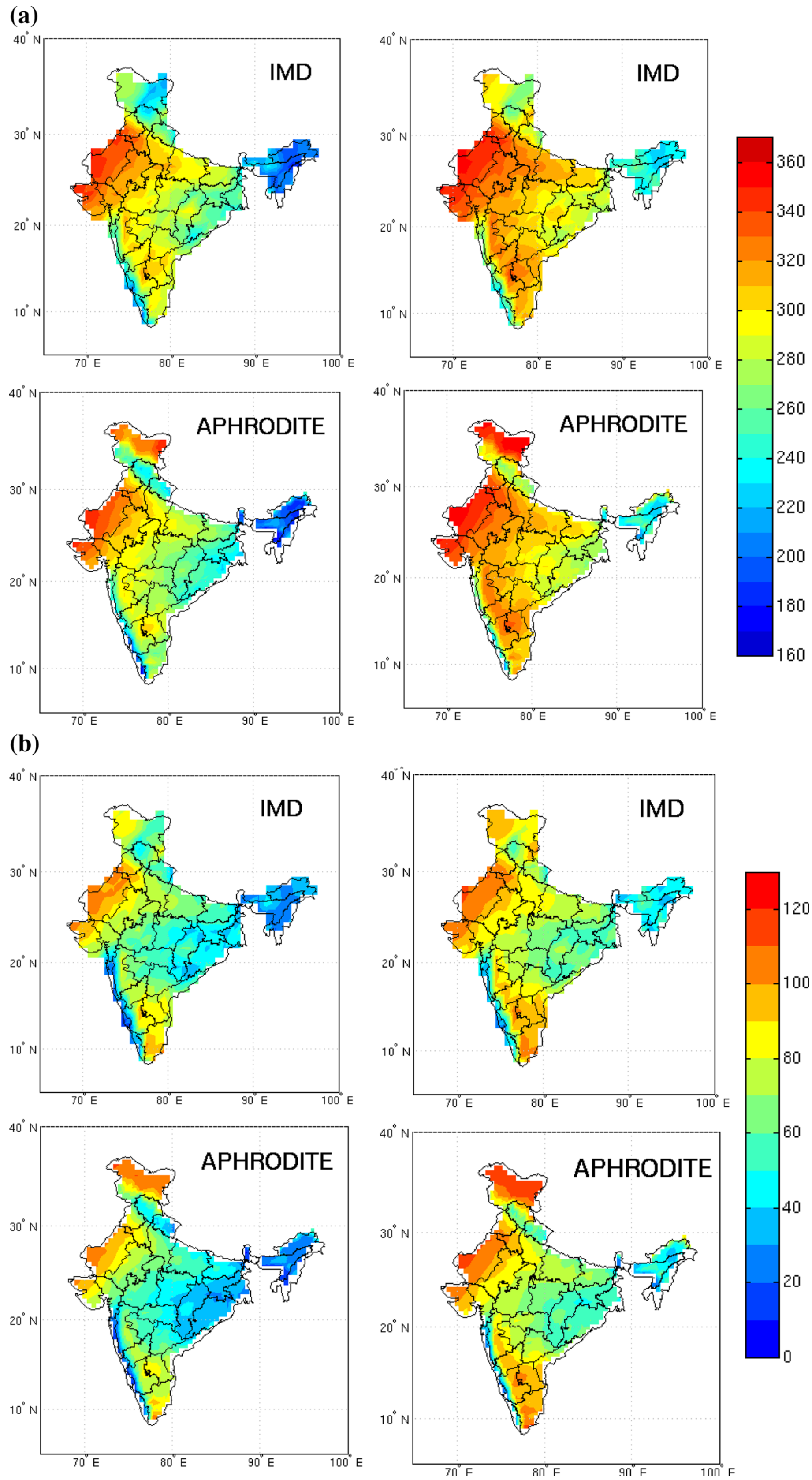
In general, the mean maximum duration of dry spells for the 1951–2007 annual period (Fig. 6a) increases from centre to northwest with values above 120 days for parts of the northwest. The mean annual maximum duration of dry spells, for example along the west coast, is associated with dry spells that clearly lie outside of the monsoon period. Similar to Figs. 4 and 5, the APHRODITE data, with respect to IMD data, shows larger values of maximum duration of dry spells in the northern part of India (Fig. 6). As for the case of mean duration, the east–west contrast in the maximum duration of dry spells over peninsular India is more notable at 3 mm threshold.

3.2 Trend analysis

3.2.1 Annual/monsoonal number of dry days

Figure 7a, b show trends (increasing/decreasing) in number of dry days at grid-cell level for annual and summer monsoon periods for the 1951–2007 period obtained using the MK test. A comparison (not shown) between the results obtained by applying the MK test with and without the correction for serial dependence suggests that the former procedure helped in overcoming spurious trend detections.

Fig. 3 Mean **a** annual and **b** summer monsoonal number of dry days for IMD (*top subpanels*) and APHRODITE (*bottom subpanels*) datasets, for 1 mm (*left panels*) and 3 mm (*right panels*) precipitation thresholds, for the 1951–2007 period. The unit is days



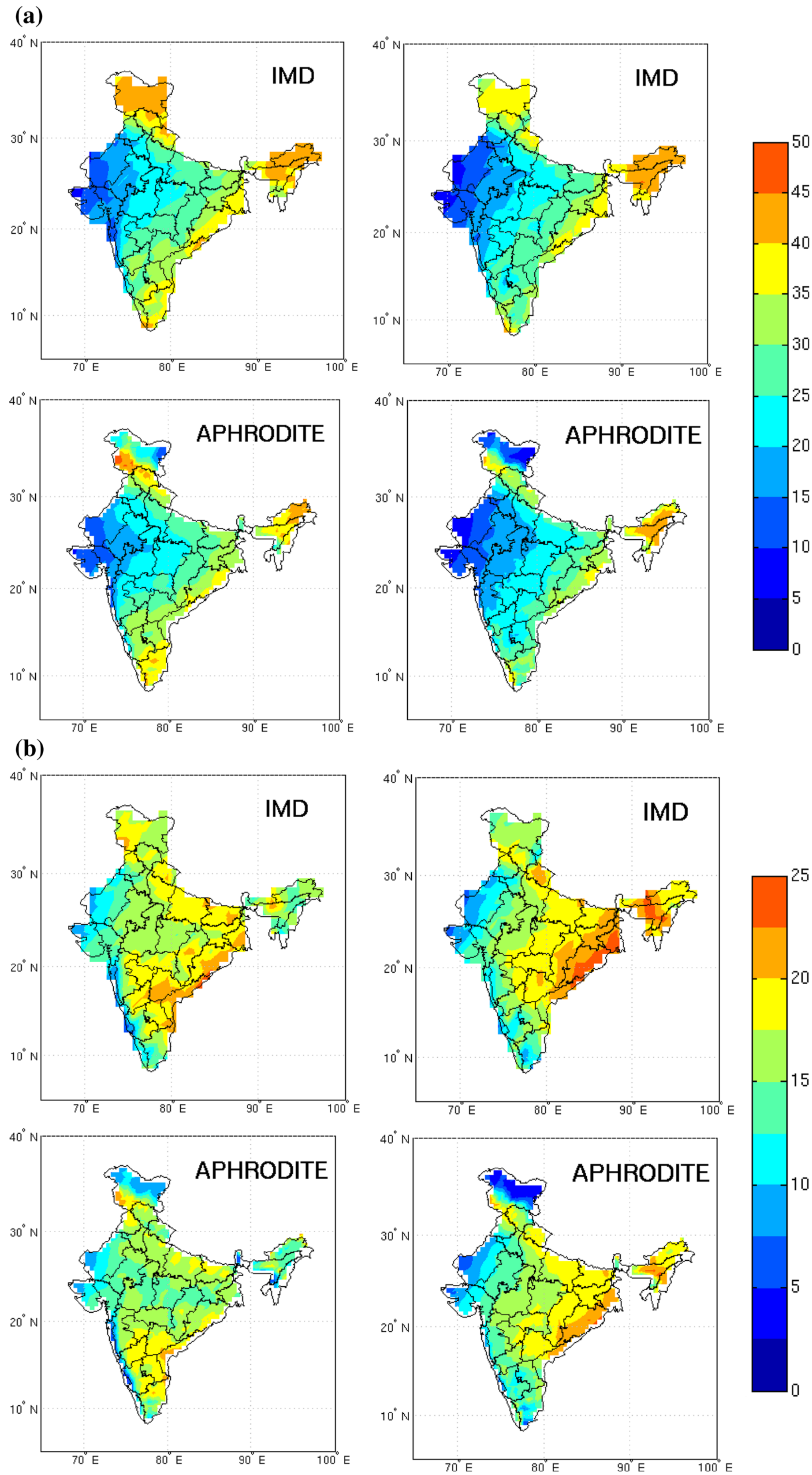


Fig. 4 Mean **a** annual and **b** summer monsoonal number of dry spells for IMD (*top subpanels*) and APHRODITE (*bottom subpanels*) datasets, for 1 mm (*left panels*) and 3 mm (*right panels*) precipitation thresholds, for the 1951–2007 period. The unit is days

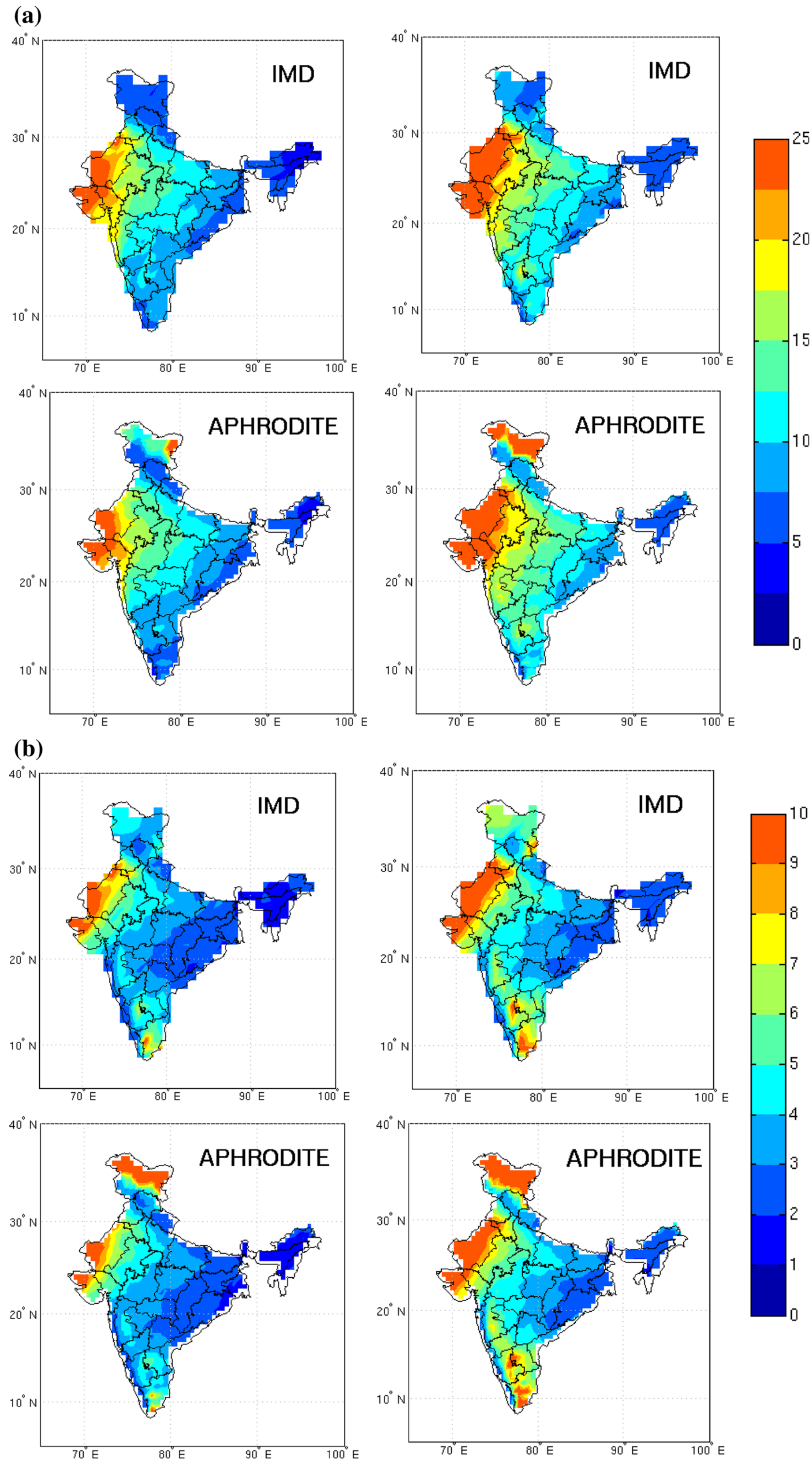


Fig. 5 Mean **a** annual and **b** summer monsoonal duration of dry spells for IMD (*top subpanels*) and APHRODITE (*bottom subpanels*) data, for 1 mm (*left panels*) and 3 mm precipitation thresholds (*right panels*), for the 1951–2007 period. The unit is days

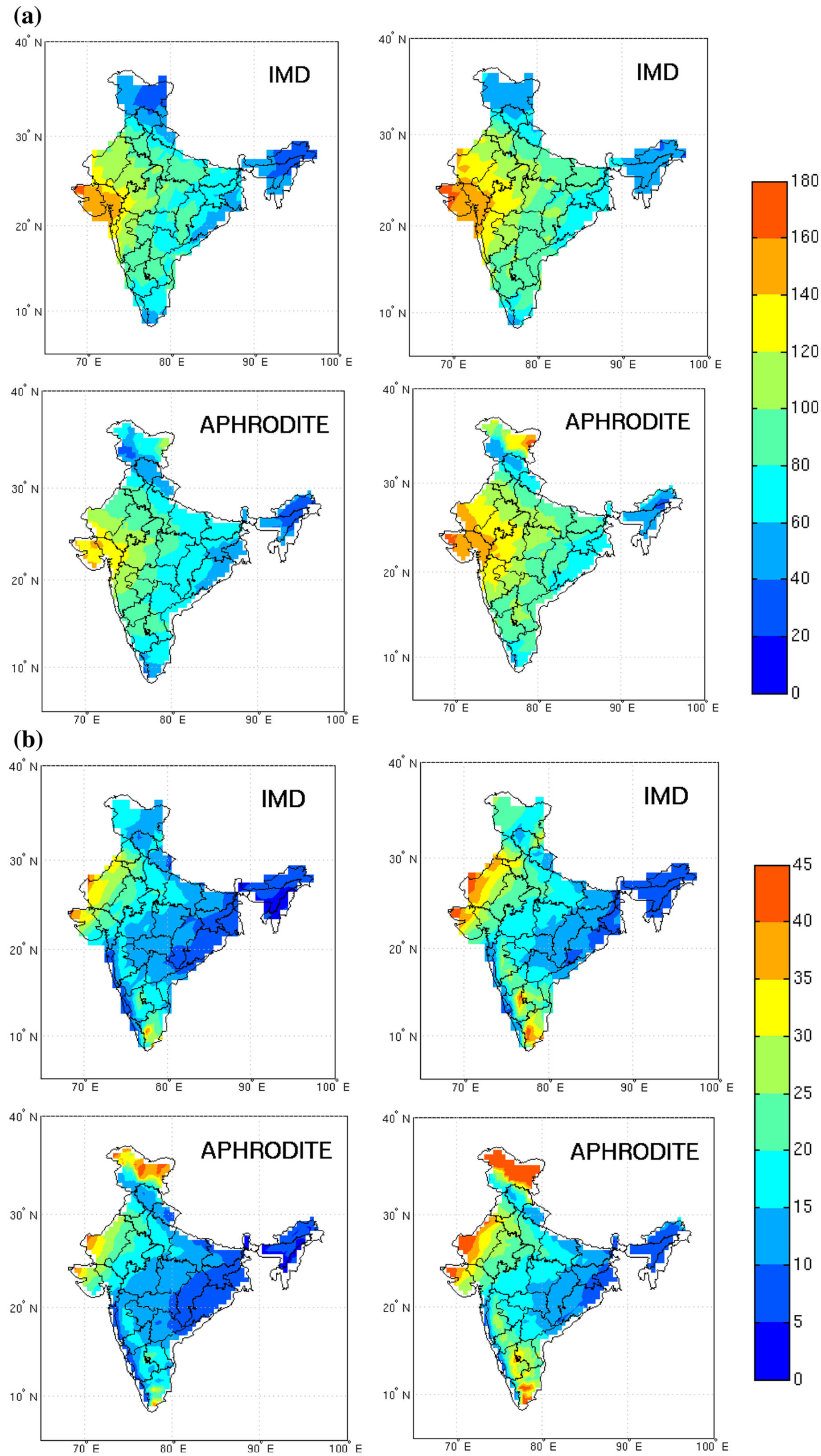


Fig. 6 Mean maximum **a** annual and **b** summer monsoonal duration of dry spells for IMD (*top subpanels*) and APHRODITE (*bottom subpanels*) datasets, for 1 mm (*left panels*) and 3 mm (*right panels*) precipitation thresholds, for the 1951–2007 period. The unit is days

Statistically significant increasing trends in number of dry days are obtained for some parts of India particularly in the central and northeast parts, for both IMD and APHRODITE datasets. However, significant decreasing trends are noted over a few parts mostly around 12°N–15°N in peninsular area (south Karnataka and Rayalaseema), over West Bengal

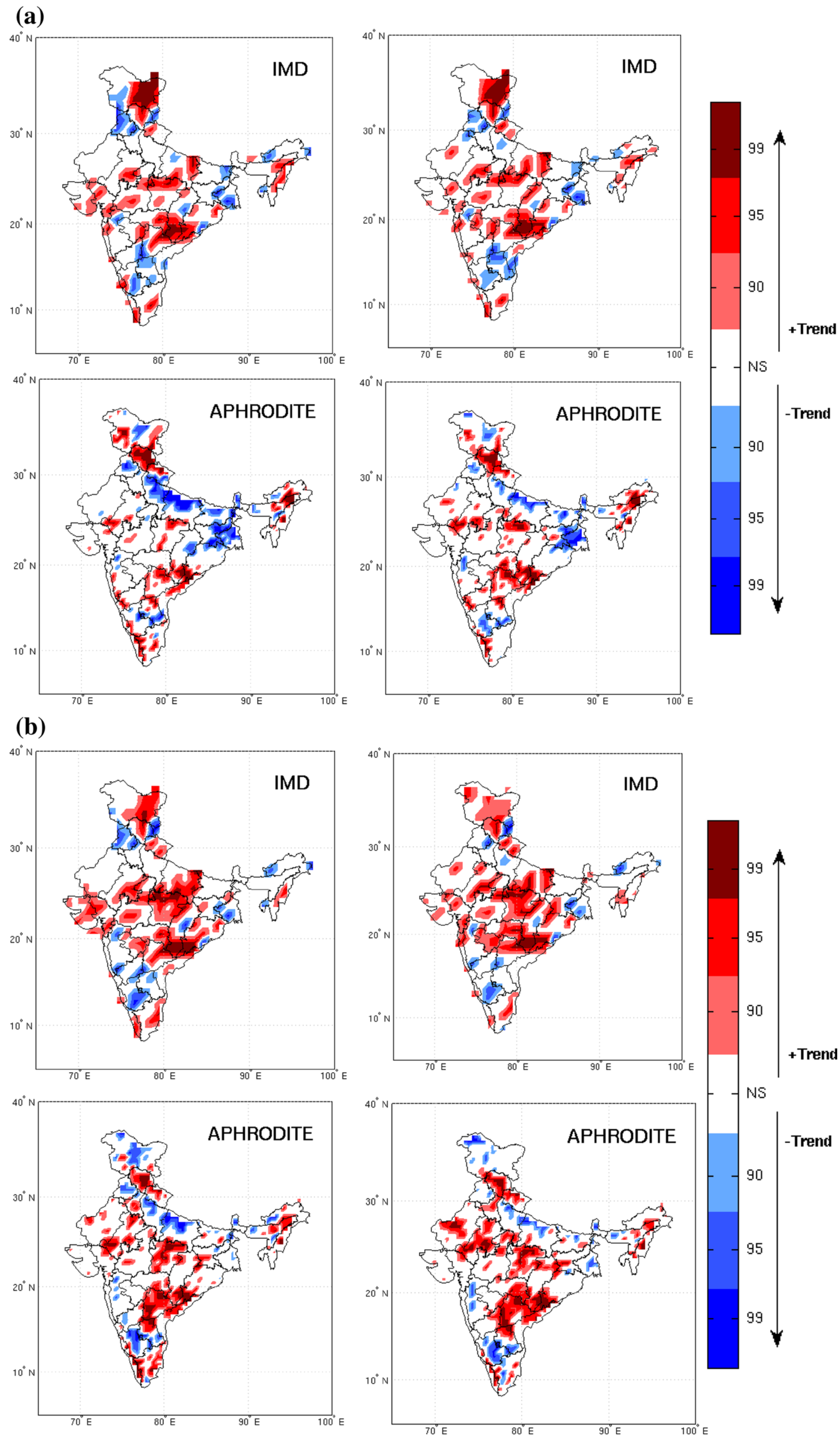


Fig. 7 Trends in **a** annual and **b** summer monsoonal number of dry days for IMD (*top subpanels*) and APHRODITE (*bottom subpanels*) datasets, for 1 mm (*left panels*) and 3 mm (*right panels*) precipitation thresholds, for the 1951–2007 period

in the eastern region and over Punjab in northwest area. Though the two datasets seem to agree for the central part of India, APHRODITE data shows significant decreasing trends in number of dry days along the foothills of the Himalaya range. This is not the case with IMD. Most parts of the northernmost area of India (Jammu and Kashmir) show mainly increasing trend for IMD data and some decreasing trends with APHRODITE data, because of the difference in precipitation patterns over this region. For 3 mm threshold, the patterns are almost similar to those for 1 mm threshold for both datasets. However, the significant decreasing trends along the Himalayas for APHRODITE are less prominent for 3 mm threshold compared to 1 mm threshold.

Trends in number of dry days for summer monsoon period (Fig. 7b) in comparison with the annual period (Fig. 7a) show similar patterns, with regions of significantly increasing trends extended in space, especially in the centre, for both datasets. The areas with significant decreasing trends along the Himalaya range for the annual period appear reduced for the monsoon period for the APHRODITE data (Fig. 7b). In general, the trend analysis of number of dry days at grid cell level suggests that some regions, particularly in the centre and southeast central parts of the country, exhibit an increasing trend in dry days, while parts of West Bengal, Punjab and regions in the 12°N–15°N in southern peninsula are associated with a decreasing trend in dry days.

As discussed in the methodology section, both binomial distribution-based and FDR approaches are used to test field significance of positive and negative trends in number of dry days for each of the 34 subdivisions. It is important to mention here that the FDR approach has recently been recommended by Wilks (2006) for field significance analysis due to its advantages over the other methods. Therefore, for the convenience of presentation, the results of the FDR approach are discussed in detail, while those of the other approach are summarized at the end of the section. The results of field significance analysis for positive and negative trends in annual and summer monsoonal number of dry days are shown in Figs. 8 and 9, respectively. The positive trends in annual number of dry days (Fig. 8a) are found to be field significant for 13 and 15 subdivisions, respectively, for IMD and APHRODITE datasets for 1 mm threshold. However, the number of common subdivisions where trends are found field significant for both datasets is only 10. (These subdivisions correspond to the regions where mostly significant trends were noted in Fig. 7a). The results for both datasets differ mostly in the northeastern part of India. At 3 mm threshold, the number of subdivisions where positive trends are field significant increases to 17 for APHRODITE dataset and remains the same for IMD dataset. Again, the differences between the two datasets are noticeable over northeast India (regions 2–4). In both datasets and for both thresholds, the northern regions (Jammu and Kashmir and Himachal Pradesh), the central east parts (Orissa, Telangana and Chattisgarh) and the extreme south peninsula (Kerala and Tamilnadu and Pondicherry) show field significant increasing trends.

FDR analysis suggests that the negative trends in annual number of dry days (Fig. 8b) are field significant for 13 subdivisions, along the Himalaya range and over the Madhya Maharashtra, Rayalaseema, South Interior Karnataka and Coastal Andhra Pradesh around 12°N–20°N in peninsular area, at 1 mm threshold, for APHRODITE, which reduces to 7 when the threshold is increased to 3 mm. For IMD dataset, the negative trends are found field significant for 6 and 5 subdivisions, for 1 and 3 mm thresholds, respectively. The differences between the IMD and APHRODITE, especially at 1 mm threshold is concentrated along the foothills of the Himalaya range, which is consistent with results presented in Fig. 7b. Comparing Fig. 8a, b, it can be seen that Orissa, Chattisgarh, Telangana and Nagaland (Himachal Pradesh, Orissa and Telangana) are subdivisions associated with field significant positive and negative trends at 1 mm (3 mm) threshold for IMD dataset. A similar comparison for APHRODITE dataset suggests that Assam and Meghalaya, West Uttar Pradesh Hills, Coastal Andhra Pradesh, and Rayalaseema (Assam and Meghalaya and Rayalaseema) are subdivisions associated with field significant positive and negative trends at 1 mm (3 mm) threshold. A close scrutiny of Fig. 7 indicates that there are clear specific regions with dominating positive and negative trend patterns within these subdivisions. This provides some explanation why both positive and negative trends are field significant within these subdivisions.

Figure 9a, b show results of field significance analysis for number of dry days for the June–September monsoon season. In general, better agreement can be noted between the two datasets, with positive trends being field significant for many subdivisions, at 1 mm threshold. At 3 mm threshold some differences are visible between the two datasets (for example, northeast regions, and southern peninsula). With respect to negative trends in number of dry days for summer monsoon period, again some differences can be noticed between the two datasets. APHRODITE suggests field significance for subdivisions along the Himalaya range, which is not the case with IMD. Similarly not all regions that appear field significant in IMD are found to be field significant with APHRODITE data. South Interior Karnataka is the only subdivision where both positive and negative trends are field significant for the APHRODITE dataset for both thresholds. With IMD, Orissa is the only subdivision where both positive and negative trends are field significant for both 1 and 3 mm thresholds.

3.2.2 Annual/monsoonal maximum duration of dry spell

Trend analysis of annual maximum duration of dry spells (Fig. 10) suggests significantly decreasing trends for northwest and northeast (West Bengal) parts of India, according to both datasets. The same analysis for the

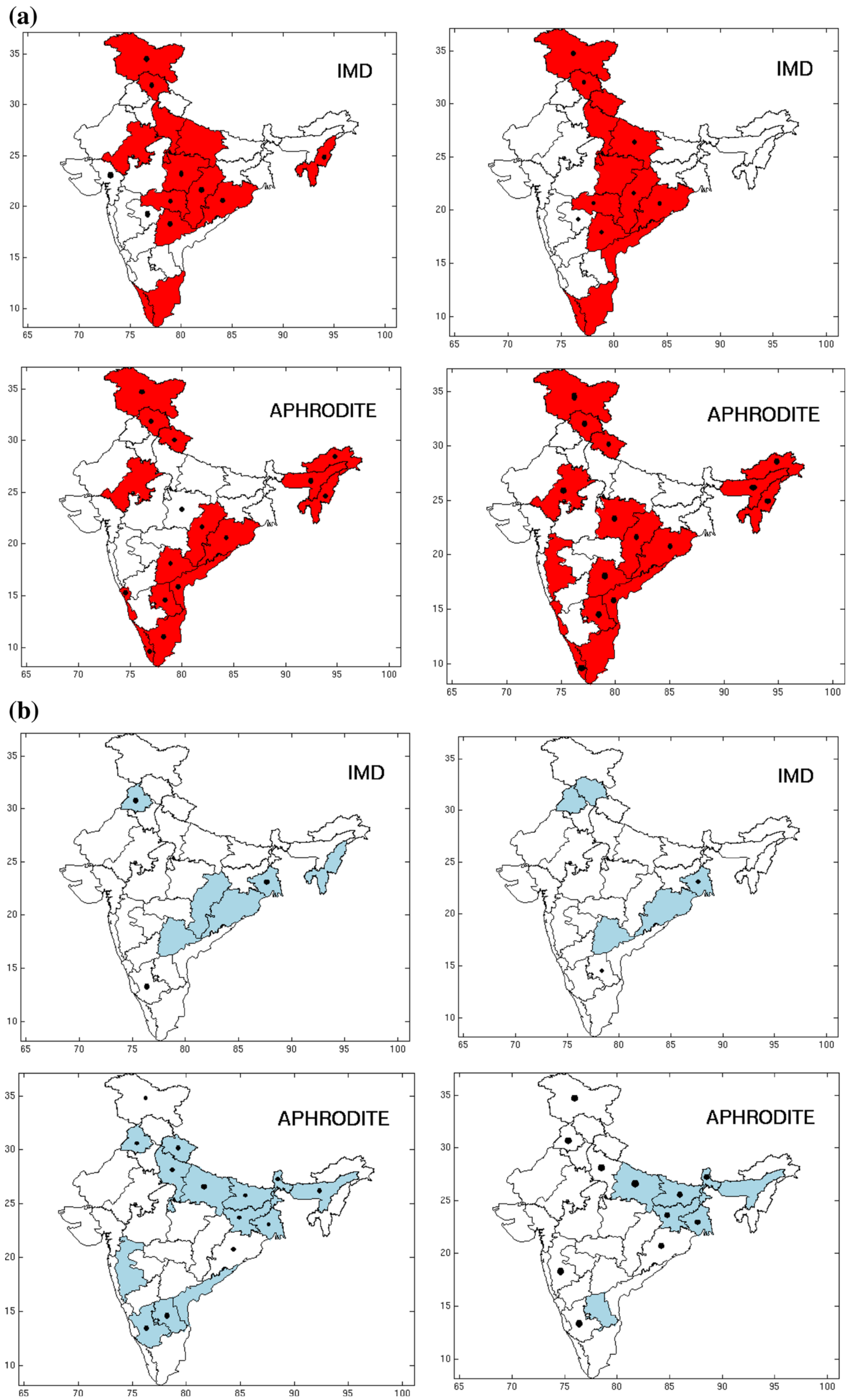


Fig. 8 Field significance of **a** positive and **b** negative trends associated with annual number of dry days for IMD (*top subpanels*) and APHRODITE (*bottom subpanels*), for 1 mm (*left panels*) and 3 mm (*right panels*) precipitation thresholds, for the 1951–2007 period. Regions with field significant positive (negative) trends are shown *shaded in red* (*blue*) for the FDR approach and using *dots* for the binomial distribution approach

monsoon period suggests different patterns than that for annual, with significant decreasing trends concentrated in the northernmost part of India and along the west coast. This suggests that the decreasing trends in the annual maximum duration of dry spells for the arid northwest is due to an increasing trend in the number of wet days outside of the monsoon season. The patterns, in general, are comparable across both datasets.

The results of field significance analysis for positive/negative trends in the annual maximum duration of dry spells are presented in Fig. 11a, b. Three subdivisions suggest positive trends to be field significant in the case of

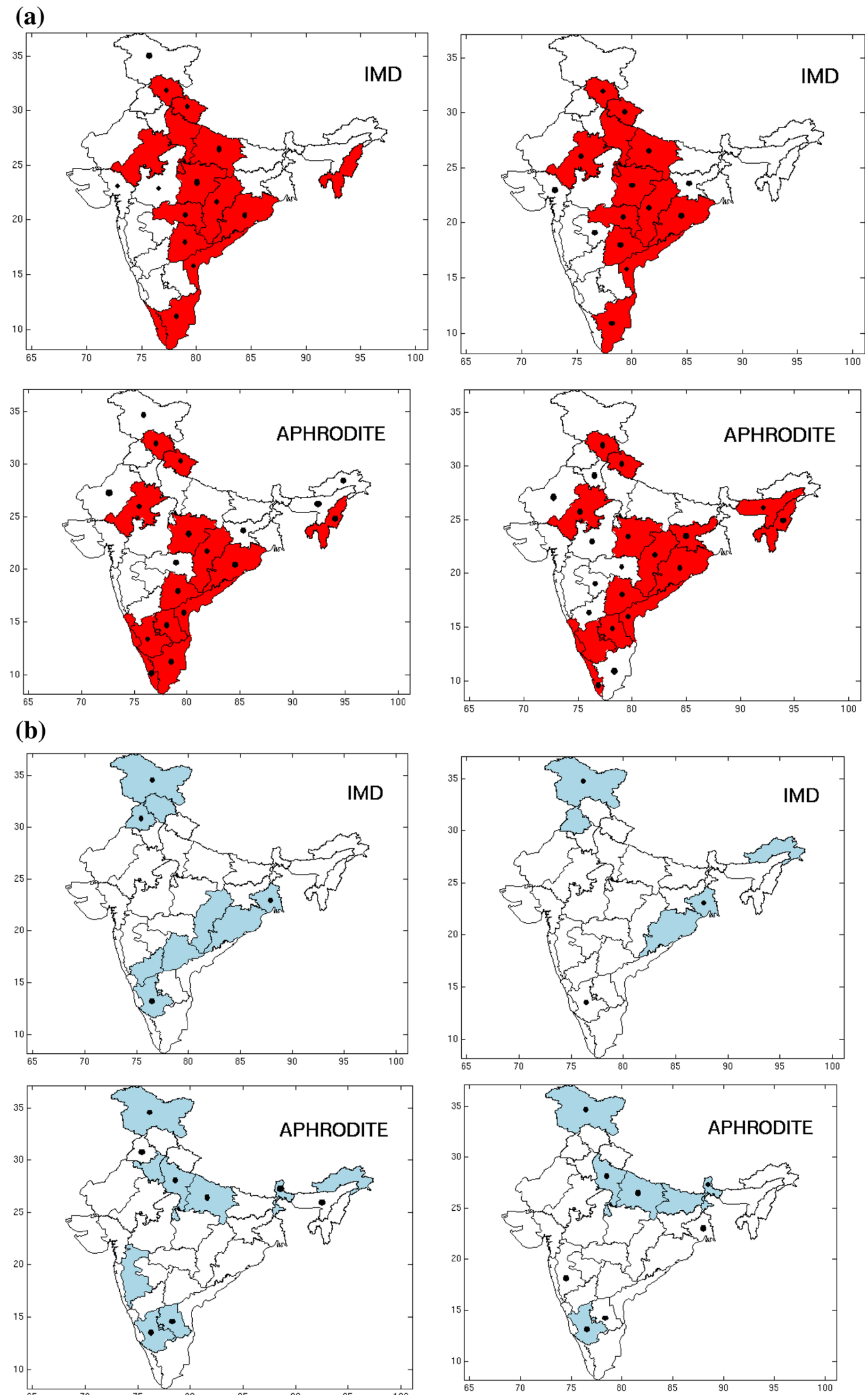


Fig. 9 Field significance of **a** positive and **b** negative trends associated with summer monsoonal number of dry days for IMD (*top subpanels*) and APHRODITE (*bottom subpanels*), for 1 mm (*left panels*) and 3 mm (*right panels*) precipitation thresholds, for the 1951–2007 period. Regions with field significant positive (negative) trends are shown *shaded in red* (*blue*) for the FDR approach and using *dots* for the binomial distribution approach

IMD at both 1 and 3 mm thresholds, with Marthwada and Himachal Pradesh being the common subdivisions. For APHRODITE, positive trends for two (three) subdivisions appear to be field significant at 1 mm (3 mm) threshold: of these two subdivisions, one (Jammu and Kashmir) is associated with field significant negative trends also. In general, though the number of subdivisions that are field significant is smaller, there is some disagreement between the two datasets, for both positive and negative trends. For negative trends, West Rajasthan is the only subdivision that is field significant at both 1 and 3 mm thresholds, for both datasets. At 3 mm threshold, the common subdivisions

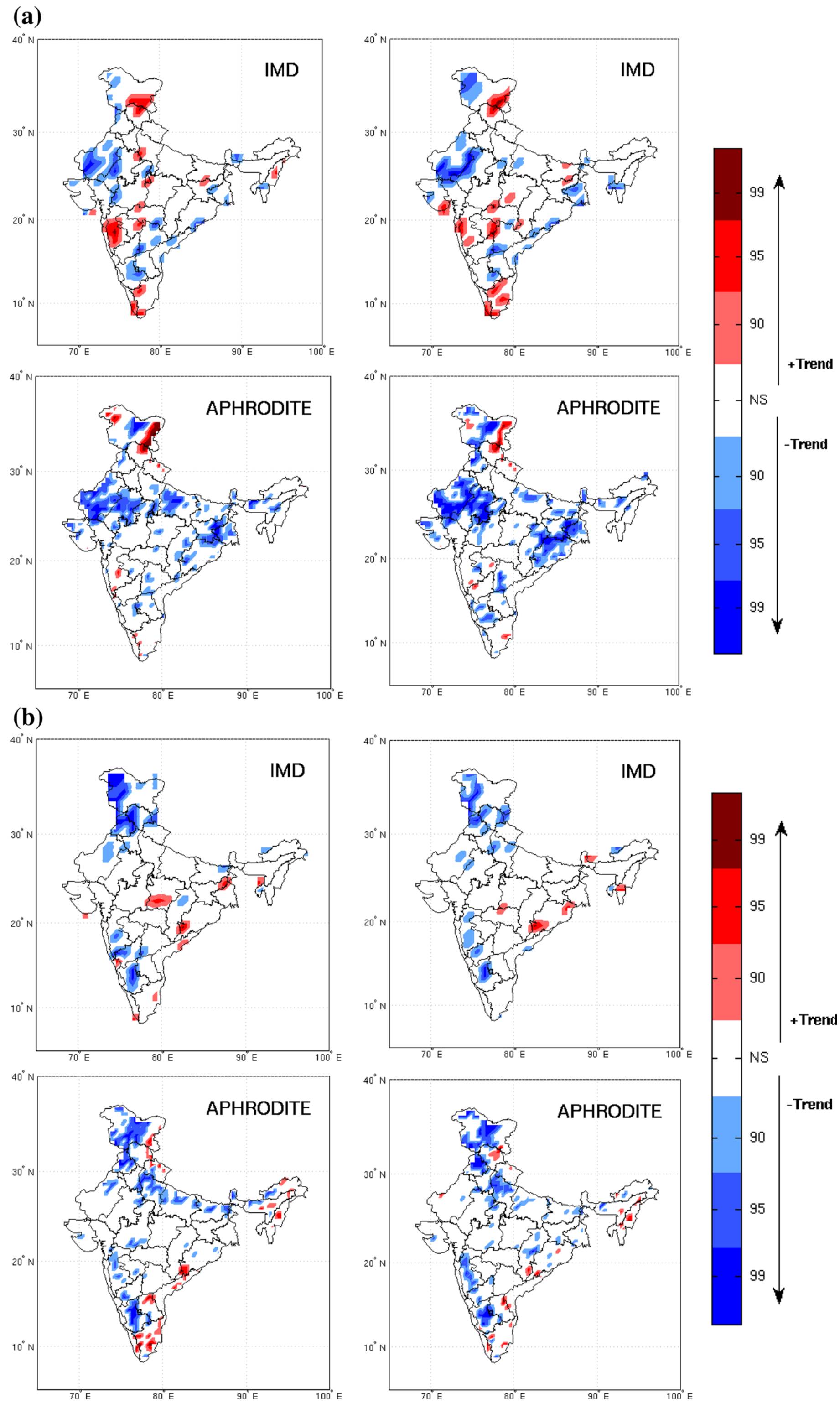


Fig. 10 Trends in **a** annual and **b** summer monsoonal maximum duration of dry spells for IMD (*top subpanels*) and APHRODITE (*bottom subpanels*) datasets, for 1 mm (*left panels*) and 3 mm (*right panels*) precipitation thresholds, for the 1951–2007 period

showing field significance are West and East Rajasthan and Telangana.

Similar analysis, focussing on maximum duration of dry spells during the June–September monsoon period, is shown in Fig. 12. Negative trends (Fig. 12b) associated with two subdivisions (South Interior Karnataka and Punjab) appear field significant for both datasets and precipitation thresholds. For positive trends (Fig. 12a), there are just one and three subdivisions that appear field significant for IMD and APHRODITE, respectively, for 1 mm

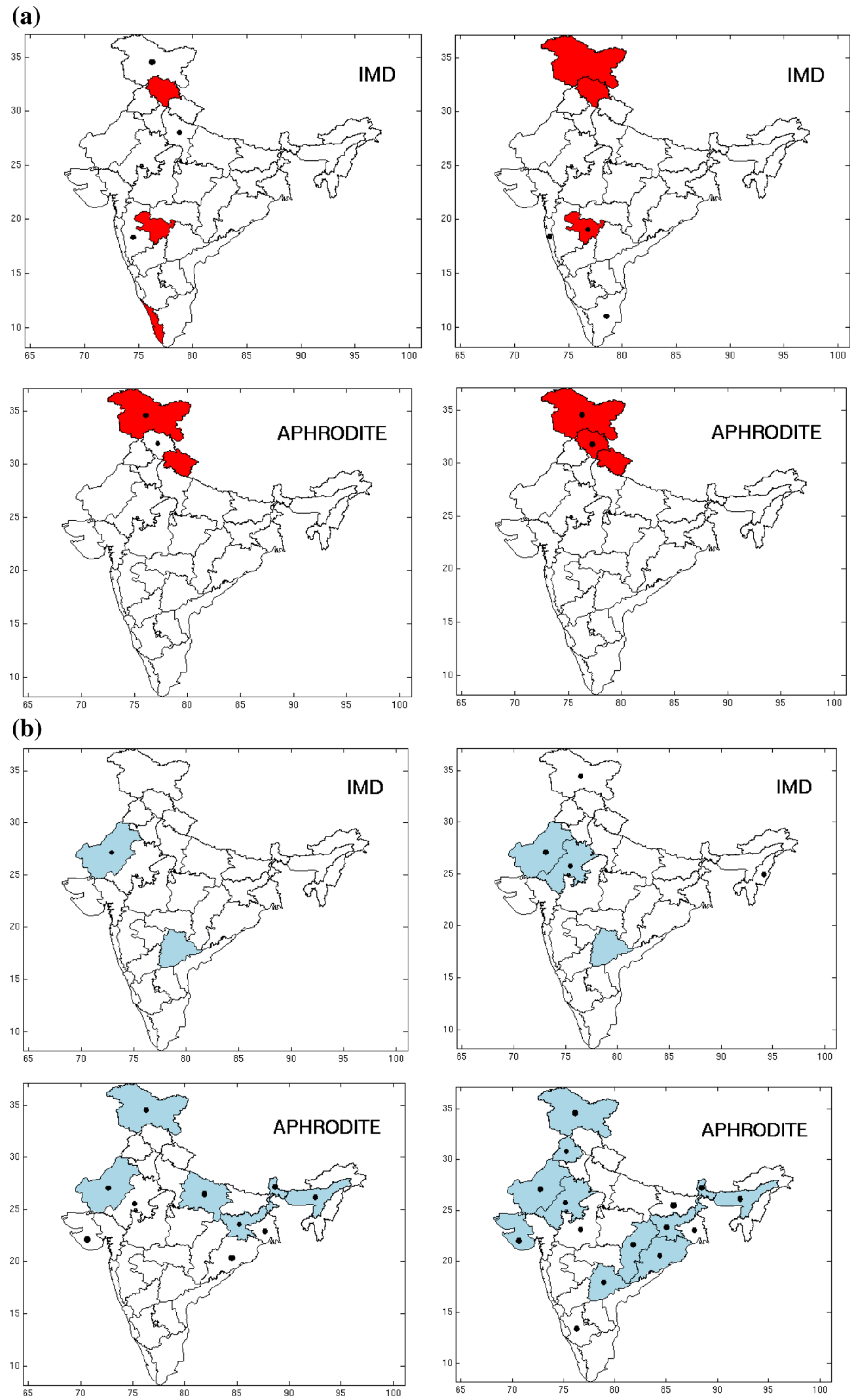


Fig. 11 Field significance of **a** positive and **b** negative trends associated with annual maximum duration of dry spells for IMD (*top subpanels*) and APHRODITE (*bottom subpanels*) datasets, for 1 mm (*left panels*) and 3 mm (*right panels*) precipitation thresholds, for the 1951–2007 period. Regions with field significant positive (negative) trends are shown *shaded in red* (*blue*) for the FDR approach and using *dots* for the binomial distribution approach

threshold. For 3 mm threshold this reduces to two, for APHRODITE.

On the basis of combined results for both IMD and APHRODITE datasets for both thresholds, Orissa, Himachal Pradesh, Chattisgarh and Telangana subdivisions show field significant increasing trends in both annual and monsoonal period number of dry days. However, no such pattern was found for the case of decreasing trends and for the case of both increasing/decreasing trends in both annual and monsoonal period maximum duration of dry spells. When a similar synthesis is carried out for the annual and monsoonal periods separately, Himachal Pradesh and

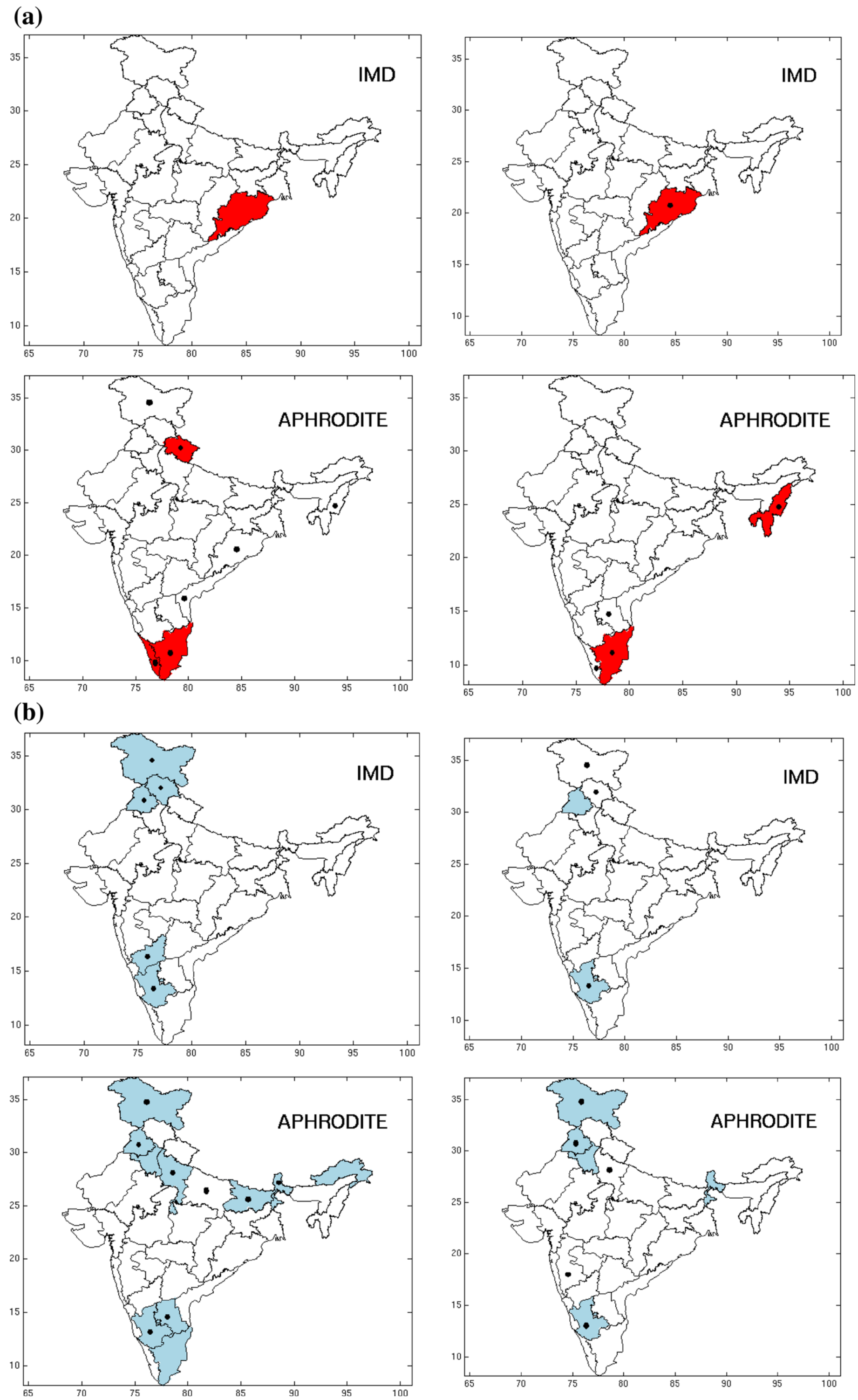


Fig. 12 Field significance of **a** positive and **b** negative trends associated with summer monsoonal maximum duration of dry spells for IMD (*top subpanels*) and APHRODITE (*bottom subpanels*) datasets, for 1 mm (*left panels*) and 3 mm (*right panels*) precipitation thresholds, for the 1951–2007 period. Regions with field significant positive (negative) trends are shown *shaded in red* (*blue*) for the FDR approach and using dots for the binomial distribution approach

Jammu and Kashmir (South Interior Karnataka and Jammu and Kashmir) show higher number of cases with field significant increasing (decreasing) trends in both annual (monsoonal period) number of dry days and maximum duration of dry spells. No regions are found to show consistent field significant increasing trends in both maximum duration of dry spells and number of dry days for the monsoon period. The two datasets in fact disagree with respect to the regions showing field significant increasing trends in monsoonal maximum duration of dry spells. It is important to mention that a similar synthesis, across datasets and thresholds, suggests field significant decreasing trends in annual maximum duration of dry spells for the north-westernmost part of India (West Rajasthan). However, the decreasing trends associated with the annual number of dry days for this region are not found field significant. Guhathakurta and Rajeevan (2008) based on their analysis of rain gauge data, for a longer period (1901–2005), also found that the great desert areas of India, including West Rajasthan, have become wetter.

As far as the results of the two methods of field significance analysis (i.e. the binomial distribution based approach and FDR method) are concerned, the level of agreement among the results of these methods is higher for APHRODITE based characteristics compared to those based on IMD dataset. Though the results of both methods differ from each other for about 40 % cases, no new other overall patterns of field significance emerged than those presented above even by using the results of the method based on the binomial distribution.

4 Summary and conclusions

The dry spell characteristics over India during the 1951–2007 period are explored using two gridded datasets—IMD and APHRODITE. The dry spell is defined as a continuous period of dry days, where a dry day is defined using two precipitation thresholds—1 and 3 mm. The characteristics considered include the number of dry days, number of dry spells, mean and maximum dry spell durations, for both annual and summer monsoonal (JJAS) periods. Spatial patterns of these characteristics are studied based on the two datasets. In addition trends in the annual/summer monsoonal number of dry days and annual/summer monsoonal maximum duration of dry spells are also analysed using a modified nonparametric MK test. To help synthesise results, field significance of identified positive and negative trends is assessed at the level of pre-defined 34 subdivisions over India using the binomial distribution and FDR approaches. The most important results are summarized below.

- The spatial patterns of mean annual and mean summer monsoonal precipitation for the 1951–2007 period are generally very similar for the IMD and APHRODITE datasets, except for the northernmost part of India. This could be partly due to the differences in the underlying data sources used in the two datasets for this region. However, more spatial detail emerges with the high resolution APHRODITE dataset.
- The spatial patterns of mean number of dry days follow inverse pattern of precipitation, with maximum number of dry days along the northwest part of India for both annual and summer monsoon periods.
- Mean annual number of dry spells is relatively higher along the east coast of India, though of short duration due to larger number of rainy days. Similar pattern is noted for the summer monsoon period.
- Mean annual duration of dry spells is larger over the arid regions in the northwest, with values reaching above 20 days. Spatial patterns are similar for the monsoon period, with mean values of dry spell durations of the order of 10 days for the northwest regions. The east–west contrast in the mean duration of dry spells for the monsoon period over peninsular India is clearly captured in both datasets, particularly at 3 mm threshold.
- Annual maximum duration of dry spells varies from greater than 150 days in the northwest to below 20 days in the northeast. The maximum duration of dry spell during the monsoon period in the rainshadow zones in the leeward side of the Western Ghats is similar to that for the northwest regions.
- Trend analysis of annual number of dry days at grid-cell level shows some differences between the two datasets. The important difference is noted along the Himalaya range, where APHRODITE suggests significant decreasing trends, which does not show up with IMD dataset.
- Analysis of annual maximum duration of dry spells suggests significant decreasing trends for the northwest part of India. This signal is not present in the analysis of maximum duration of dry spells for the summer monsoon period.
- The field significance analysis performed for positive and negative trends in number of dry days and maximum duration of dry spells for the annual and summer monsoon periods helps identify regions where trends are found beyond those expected due to coincidence. However, the results of this analysis are not only dependent on the type of the gridded dataset and annual and monsoonal time windows, but also on the threshold used to define dry days and therefore dry spells.

This study helps in identifying regions and characteristics of dry spells where important differences exist between the IMD and APHRODITE datasets, which is particularly visible in the trend analysis results. These results will thus provide useful insights for the climate modelling community in establishing appropriate benchmarks for performing model evaluation, specifically over the Indian landmass, given the recent increase in regional climate model and statistical downscaling applications over the region (e.g. Saeed et al. 2011; Lucas-Picher et al. 2011; Vigaud et al. 2012).

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References

Beniston M, Stephenson DB, Christenson OB, Ferro CAT, Frei C, Goyette S, Halsnaes K, Holt T, Jylhä K, Koffi B, Palutikof J, Schöll R, Semmler T, Woth K (2007) Future extreme events in European climate: an exploration of regional climate model projections. Clim Change 81:71–95

Bouagila B, Sushama L (2013) On the current and future dry spell characteristics over Africa. Atmosphere 4:272–298

Cohn TA, Lins HF (2005) Nature's style: naturally trendy. Geophys Res Lett 32:L23402. doi:10.1029/2005GL024476

Elmore KL, Baldwin ME, Schultz DM (2006) Field significance revisited: spatial bias errors in forecasts as applied to the Eta model. Mon Weather Rev 134:519–531

Ghosh S, Luniya V, Gupta A (2009) Trend analysis of Indian summer monsoon rainfall at different spatial scales. Roy Meteorol Soc 10(4):285–290

Gong DY, Shi PJ, Wang JA (2004) Daily precipitation changes in the semi-arid region over northern China. J Arid Environ 59:771–784

Goswami BN, Venugopal V, Sengupta D, Madhusoodanan MS, Prince KX (2006) Increasing trend of extreme rain events over India in a warming environment. Science 314:1442–1445

Guhathakurta P, Rajeevan M (2008) Trends in the rainfall pattern over India. Int J Climatol 28(11):1453–1469

Hamed KH, Rao AR (1998) A modified Mann-Kendall trend test for autocorrelated data. J Hydrol 204:219–246

Joshi UR, Rajeevan M (2006) Trends in precipitation extremes over India. National Climate Centre, Pune

Kendall MG (1975) Rank correlation methods. Charles Griffin, London

Khaliq MN, Ouarda TBMJ, Gachon P, Sushama L, St-Hilaire A (2009a) Identification of hydrological trends in the presence of serial and cross correlations: review of selected methods and their application to annual flow regimes of Canadian rivers. J Hydrol 368(1–4):117–130

Khaliq MN, Ouarda TBMJ, Gachon P (2009b) Identification of temporal trends in annual and seasonal low flows occurring in Canadian rivers: the effect of short- and long-term persistence. J Hydrol 369:183–197

Lucas-Picher P, Christensen JH, Saeed F, Kumar P, Asharaf S, Ahrens B, Wiltshire AJ, Jacob D, Hagemann S (2011) Can regional climate models represent the Indian monsoon? J Hydrometeor 12:849–868

Kulkarni A, von Storch H (1995) Monte Carlo experiments on the effect of serial correlation on the Mann-Kendall test of trend. Meteorol Z 4(2):82–85

Lana X, Burgueno A, Martinez MD, Serra C (2006) Statistical distributions and sampling strategies for the analysis of extreme dry spells in Catalaonia (NE Spain). J Hydrol 324:94–114

Livezey RE, Chen WY (1983) Statistical field significance and its determination by Monte Carlo techniques. Mon Weather Rev 111:46–59

Mann HB (1945) Non-parametric tests against trend. Econometrica 13:245–259

May W (2008) Potential future changes in the characteristics of daily precipitation in Europe simulated by the HIRHAM regional climate model. Clim Dyn 30:581–603

Rajeevan M, Bhate J (2009) A high resolution daily gridded rainfall dataset (1971–2005) for meso-scale meteorological studies. Curr Sci 96(4):558–562

Rajeevan M, Bhate J, Kale JD, Lal B (2006) High resolution daily gridded rainfall data for the Indian region, analysis of break and active monsoon spells. Curr Sci 91(3):296–306

Rajeevan M, Bhate J, Jaswal AK (2008) Correction to "Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data". Geophys Res Lett 35:L23701. doi:10.1029/2008GL036105

Ray KCS, Srivastava AK (2000) Is there any change in extreme events like heavy rainfall? Curr Sci 79(2):155–158

Revadekar JV, Preethi B (2011) Statistical analysis of the relationship between summer monsoon precipitation extremes and food grain yield over India. Int J Climatol 1–10. doi: 10.1002/joc.2282

Saeed F, Hagemann S, Jacob D (2011) A framework for the evaluation of the South Asian summer monsoon in a regional climate model applied to REMO. Int J Climatol 32:430–440

Serra C, Burgueno A, Martinez MD, Lana X (2006) Trends in dry spells across Catalonia (NE Spain) during the recent half of the 20th century. Theoret Appl Climatol 85:165–183

Shepard D (1968) A two-dimensional interpolation function for irregularly spaced data. In Proceedings of 1968 ACM national conference, pp 517–524

Singh N, Ranade A (2010) The wet and dry spells across India during 1951–2007. J Hydrometeorol 11:26–45

Subbaramayya I, Naidu CV (1992) Spatial variations and trends in the Indian monsoon rainfall. Int J Climatol 12:597–609

Suppiah R, Hennessy KJ (1998) Trends in total rainfall, heavy rain events and number of dry days in Australia, 1910–1990. Int J Climatol 10:1141–1164

Sushama L, Khaliq MN, Laprise R (2010) Dry spell characteristics over Canada in a changing climate as simulated by the Canadian RCM. Global Planet Change 74:1–14

Tebaldi C, Hayhoe K, Arblaster JM, Meehl GA (2006) Going to the extremes: an intercomparison of model-simulated historical and future changes in extreme events. Clim Change 79:185–211

Uma R, Lakshmi Kumar TV, Narayanan MS, Rajeevan M, Bhate J, Niranjan Kumar K (2013) Large scale features and assessment of spatial scale correspondence between TMPA and IMD rainfall datasets over Indian landmass. J Earth Syst Sci 122(3):573–588

Ventura V, Paciorek CJ, Risbey JS (2004) Controlling the proportion of falsely rejected hypotheses when conducting multiple tests with climatological data. J Clim 17:4343–4356

Vigaud N, Vrac M, Caballero Y (2012) Probabilistic downscaling of GCM scenarios over southern India. Int J Climatol. doi:10.1002/joc.3509

Wang XL, Swail VR (2001) Changes of extreme wave heights in northern hemisphere oceans and related atmospheric circulation regimes. J Clim 14:2204–2221

Wilks DS (2006) On "field significance" and false discovery rate. J Appl Meteorol Climatol 45:1181–1189

Yatagai A, Arakawa O, Kamiguchi K, Kawamoto H, Nodzu MI, Hamada A (2009) A 44-years daily gridded precipitation dataset for Asia based on dense network of rain gauges. SOLA 5:137–140. doi:10.2151/sola.2009-035

Yue S, Pilon P, Phinney B (2003) Canadian streamflow trend detection: impacts of serial and cross-correlation. Hydrol Sci J 48(1):51–63