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Innovative and polygonal trend analysis of temperature in agro climatic zones of India

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Understanding the long-term trends in temperature is crucial for assessing the impacts of climate change on agriculture, human and animal health, and natural habitats. An in-depth analysis of long-term spatio-temporal trends of monthly maximum and minimum temperatures along with Diurnal Temperature Range (DTR) from 1951 to 2022 in various Agro-Climatic Zones (ACZs) of India was performed using newly introduced Innovative Polygonal Trend Analysis (IPTA) and Innovative Trend Analysis (ITA) along with traditional Mann-Kendall (MK) or modified Mann-Kendall (m-MK) tests. The MK/m-MK and IPTA assessments detected significant trends in 44.6% and 86% of the time series data, respectively, while the ITA method detected significant trends in every time series data. The southern, western, and central parts of India are consistently experiencing rising monthly maximum and minimum temperatures. The western dry region, Central Plateau & Hills, East Coast Plains & Hills, Gujarat Plains & Hills, West Coast Plains & Hills, Southern Plateau & Hills, Western Plateau & Hills and Eastern Himalayan Region predominantly show increasing trends in both maximum and minimum temperatures in all months. The Indo-Gangetic Plains (Middle, Trans, Upper and Lower) exhibit decreasing trends in maximum temperatures during January, February, May, and June. The DTR showed increasing trends in the northern and western parts, while it has increasing trends in the central and southern parts of the country. The results of this study provide valuable information to assist in precise and informed decision-making on agricultural resource management and socio-economic policies.

Keywords Climate change, IPTA, ITA, Mann–Kendall, Sen's slope, Trend maps

The year 2023 was recorded as the warmest year globally, soaring at approximately 1.45 °C global average near-surface temperature, closest to 1.5 °C of the Paris agreement[1]. At the same time, the number of acutely food insecure individuals worldwide has more than doubled, surging from 149 million before the COVID-19 pandemic to a staggering 333 million in 2023[2]. While weather and climate extremes may not be the sole cause, they are exacerbating factors, compounding the challenges faced by vulnerable communities[3–5]. For agriculturally vital nations like India, where the agricultural sector sustains millions, understanding and addressing long-term temperature trends becomes even more crucial to alleviating the impacts of climate change on food security and livelihoods.

In contemporary research, the Mann–Kendall (MK) and modified Mann-Kendall (m-MK) tests with Sen's slope (SS) are extensively employed in trend analysis of meteorological variables[6–13]. However, their application necessitates certain assumptions regarding the data quality, like normal distribution and independence from autocorrelation[14]. A novel trend analysis approach called the Innovative Trend Analysis (ITA) method was introduced by Şen[15], which enables a graphical assessment of trends in time series data without imposing any specific assumptions. Also, the visualization of trends using ITA offers a unique advantage in understanding trends across high, medium, and low values within the dataset. ITA has been extensively used to identify trends in meteorological variables across diverse regions globally[16–20]. However, these methods, including the ITA, do not capture periodic trends, such as monthly variations, essential for understanding seasonal trend behaviors[21]. The newly introduced Innovative Polygonal Trend Analysis (IPTA) was utilized in our study to address this gap. IPTA involves partitioning a data series into two distinct subsets, subsequently subjecting them to comparative analysis, which provides more practical graphical and numerical information on the trends between successive

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months, their slopes and lengths, homogeneities, isotropies, etc[21]. The IPTA was recently utilized by researchers across the globe to visualize the trend of meteorological parameters[22–25].

Detecting trends comprehensively through the aforementioned parametric and non-parametric methods is crucial for effectively detecting trends in time series data[21,26]. Despite this necessity, only a few studies from India have adopted this approach. To the best of our knowledge, none of the studies have employed IPTA to detect trends across India, except for very few regional studies.

With this background, we planned our work with objectives to analyze and map the trends in monthly maximum and minimum temperature time series data along with Diurnal Temperature Range (DTR) of 72 years (1951–2022) for agro-climatic zones of India using MK, m-MK, SS, ITA and IPTA tests. This paper stands out due to its examination of Sen's innovative and polygonal trend test compared to the MK analysis. Unlike previous studies in the same area, it emphasizes the importance of analyzing a broader geographical area with comprehensive statistical methods to gain a deeper insight into the changing temperature patterns across both spatial and temporal dimensions.

Materials and methods
Study area and data
India, positioned as the seventh largest nation globally, lies north of the equator, extending from 8° 4′ N to 37° 6′ N in latitude and 68° 7′ E to 97° 25′ E in longitude. India has been divided into 15 Agro-Climatic Zones (ACZs) delineated according to various physical factors such as soil type, cropping patterns, rainfall distribution, irrigation development, topography, geological structure, and mineral resources[27]. This paper analyzes the temperature trends of 14 mainland ACZs in India (Fig. 1). In the current study, daily 1° × 1° resolution gridded temperature data (maximum and minimum) of 1951–2022 (72 years) developed by the India Meteorological Department (IMD) was utilized[28]. The dataset included temperature readings from 395 quality-controlled and evenly distributed ground stations until 2007, with subsequent data from 2008 onwards derived from approximately 180 stations. Subsequently, the daily maximum and minimum temperature data were processed to calculate the mean monthly temperatures for each district. The diurnal temperature range (DTR) was also calculated from the grid data as the difference of maximum and minimum temperature[29].

Methodology
The MK, m-MK, SS estimator, ITA, and IPTA methods were used to analyze trends and their magnitude of monthly maximum and minimum temperatures. At the same time, the ITA was utilized to study the trends of monthly DTR.

Mann–Kendall (MK)/modified Mann–Kendall (m-MK) method and Sen's slope (SS) estimator
The rank-based MK test[30,31] is used to detect significant trends in the temperature time series data[5]. The trends of meteorological time series data are frequently affected by autocorrelation[32].

m-MK test incorporating variance correction approach[33] was used for datasets exhibiting autocorrelation. Statistically significant lag-1 autocorrelation coefficient (ACC) in the data was determined utilizing the methodology outlined by Shahin et al.[34] and Haan[35] with significance tested at 5% levels. If the ACC was statistically significant, the m-MK test was employed to identify the trends[36]. Conversely, the m-MK test was not utilized for data lacking significant autocorrelation. In both the MK and m-MK tests, positive and negative
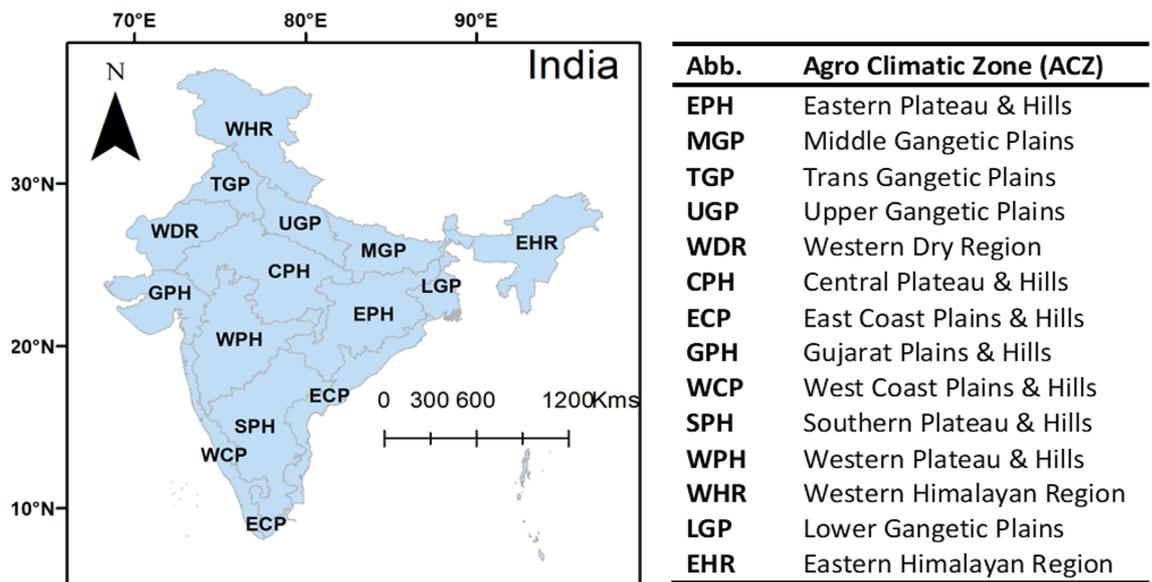

Abb.	Agro Climatic Zone (ACZ)
EPH	Eastern Plateau & Hills
MGP	Middle Gangetic Plains
TGP	Trans Gangetic Plains
UGP	Upper Gangetic Plains
WDR	Western Dry Region
CPH	Central Plateau & Hills
ECP	East Coast Plains & Hills
GPH	Gujarat Plains & Hills
WCP	West Coast Plains & Hills
SPH	Southern Plateau & Hills
WPH	Western Plateau & Hills
WHR	Western Himalayan Region
LGP	Lower Gangetic Plains
EHR	Eastern Himalayan Region

Fig. 1. Study area map showing 14 main land ACZ's of India. Created by ArcGIS Desktop v 9.1. https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview.

values of the standardized test statistics (Z_{MK} and Z_{m-MK}) signify increasing and decreasing trends, respectively. SS was employed to compute trend magnitude[37,38]. A positive SS signifies an increasing trend, while a negative SS denotes a decreasing trend in the time series data. The results in this study were statistically tested at a significance level of 5% ($\alpha = 5\%$), corresponding to Z-values of ± 1.96.

Innovative trend analysis (ITA)
The ITA was employed to identify the trends in temperature data[15]. Unlike traditional methods like the MK/ m-MK and SS, the ITA does not rely on normality, serial correlation, or record length assumptions. In the ITA method, the time series is equally partitioned into two parts, sorted in ascending order, and plotted on a Cartesian coordinate system, where the first and second halves are plotted along the X- and Y-axes, respectively. If the data points cluster along the 1:1 line, it suggests the absence of a trend. Points above this line indicate a positive trend, while points below suggest a negative trend. The positive or negative slope of the ITA (SITA), introduced by Şen[39], indicates increasing or decreasing trends, respectively. Additionally, the ITA also delineates high, medium, and low-value classes within the time series data. This feature enhances the interpretability of trends by providing insights into variations across different levels of the variable.

Innovative polygon trend analysis (IPTA)
Even with the ITA method in place, there is still a gap in capturing periodical trends, especially those occurring on a monthly basis, which is crucial for understanding seasonal trend behaviors. To bridge this gap, the IPTA was recently introduced by Şen et al.[21], built upon the foundation laid by the ITA approach of Şen[15]. IPTA identifies visual trends between successive months, including lengths and slopes. The timeframe used for this method can vary, including daily, monthly, or yearly options. We examined monthly maximum and minimum temperatures in the current work. The construction of the polygon involves plotting the averages of the first and second half of temperature data for each month on x- and y-axes, respectively. If the plotted points fall either above or below the 1:1 line, it indicates notable increasing or decreasing trends, respectively.

Results and discussion
Trends and their magnitudes
The trends and their magnitudes detected by MK/m-MK and ITA for maximum and minimum temperatures are presented in Tables 1 and 2, respectively. The graphical trend results obtained from ITA and IPTA are for maximum temperature is presented in Figs. 2 and 3 and its spatial variability mapped using MK/ m-MK and ITA methods are presented in Figs. 4 and 5. Similarly for minimum temperature the results of graphical trend analysis are presented in Figs. 6 and 7, while its spatial variability mapped using MK/ m-MK and ITA methods are presented in Figs. 8 and 9. The trends and magnitude of DTR, as analyzed using the ITA, were mapped in Fig. 10.

Maximum temperature
The MK/m-MK method was able to capture a lesser number of significant trends than the ITA and IPTA methods. The ITA detected significant trends in all the 168-time series tested, the IPTA detected significant trends in 86.3%, while the MK/m-MK was able to detect trends only in 49.4% of the time series tested.

EPH has significantly increasing trends in all months except May and June, which have significantly decreasing trends as per ITA results. Whereas IPTA shows a similar trend as ITA for each month except January, it shows no discernible trend. Conversely, the MK/m-MK was able to capture significantly increasing trends from July to November only. For MPG, the MK/m-MK captured a significantly decreasing trend during January and May and a significantly increasing trend from July to September. Conversely, ITA shows significantly decreasing trends during January, March, May, June, and December, while the rest of the month shows a significantly increasing trend. IPTA shows a decreasing trend during January, May, and December, while from July to November, it shows an increasing trend. In the case of TGP, under MK/m-MK, January shows a significantly decreasing trend, while August shows a significantly increasing trend. However, ITA indicates a significant decreasing trend for January, June, and December, while significantly increasing trends were detected in the rest of the months. Similarly, under IPTA, January, June, and December showed decreasing trends, while February to May and July to October show an increasing trend. UGP, with MK/m-MK, detected significant decreasing and increasing trends in January and August, respectively. In contrast, ITA identifies significant decreases in January, May, June, and December, with the remaining months showing a significant increasing trend. In January, UGP had the maximum declining trends of 2.508 and 2.647 °C/100 years, as depicted by MK/m-MK and ITA, respectively.

On the other hand, IPTA again shows a decreasing trend during January, May, June, and December, while July to October shows an increasing trend. For WDR, MK/m-MK reveal significant increasing trends only in April, May, and August, while ITA and IPTA show significant increases across all months. Similarly, CPH displays distinct trends across methods and months. Under MK/m-MK, significant increases are observed in April, August, and September, while under ITA, all months except January exhibit significant increasing trends, with January showing a significant decreasing trend. IPTA method mirrors the behavior of ITA apart from June and December when no trend was observed. ECP demonstrates consistent significant increasing trends across all months for all three methods, except for June, which shows no significant trend under MK/m-MK. Over GPH, using MK/m-MK, only March, April, June, and August, while under ITA and IPTA, all the months have significantly increasing trends, indicating a consistent upward trajectory. WCP and SPH exhibit notable similarity, with each method depicting a significant increasing trend regardless of the month except June under MK/m-MK, showing no significant trend.

MK/m-MK method over WPH depicts a significant increasing trend during April, May, August, and November. ITA and IPTA showed the same across the month except June and July under IPTA, showing no

ACZ	Parameter	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
EPH	SS	0.171	0.361	0.736	0.998	− 0.359	− 0.616	0.969*	1.111*	1.384*	1.365*	**1.673***	0.856
	SITA	0.306*	1.055*	0.424*	0.801*	− 0.537*	− 0.807*	0.964*	1.128*	1.311*	1.077*	1.614*	0.892*
MGP	SS	− 2.165*	− 0.346	0.115	− 0.058	− 2.144*	− 0.151	1.231*	**1.723***	1.273*	0.751	**0.660**	− 0.510
	SITA	− 2.461*	0.569*	− 0.274*	0.244*	− 1.632*	− 0.296*	1.243*	1.498*	1.143*	0.762*	0.915*	− 0.717*
TGP	SS	− 2.143*	− 0.112	0.345	1.608	0.256	− 1.264	**0.256**	1.121*	0.632	**0.353**	0.079	−0.636
	SITA	− 2.091*	0.384*	0.513*	2.111*	0.472*	− 1.386*	0.761*	1.122*	0.311*	0.374*	0.203*	− 0.605*
UGP	SS	− **2.508***	− 0.548	0.562	1.241	− 1.170	− 1.255	0.688	1.472*	0.846	**0.601**	− **0.058**	− 0.659
	SITA	− 2.647*	0.388*	0.324*	1.319*	− 0.832*	− 1.302*	1.065*	1.608*	0.835*	0.692*	0.270*	− 0.912*
WDR	SS	0.003	1.329	1.800	2.912*	1.672*	0.939	1.295	1.352*	**1.787**	1.156	**0.917**	0.608
	SITA	0.427*	2.062*	1.757*	2.710*	1.689*	0.942*	1.527*	1.835*	1.659*	1.236*	1.188*	0.981*
CPH	SS	− 0.837	0.110	1.080	2.114*	0.889	0.279	0.635	1.152*	1.676*	**1.187**	**0.935**	0.033
	SITA	− 0.521*	0.962*	0.778*	1.946*	0.918*	0.091*	1.012*	1.607*	1.436*	1.282*	1.221*	0.343*
ECP	SS	**1.661***	**1.346***	1.567*	1.709*	1.315*	0.630	**1.583***	**1.430***	**1.315***	**1.675***	**1.644***	**1.655***
	SITA	1.793*	1.583*	1.597*	1.450*	0.665*	0.456*	1.438*	1.207*	1.328*	1.406*	1.621*	1.579*
GPH	SS	0.064	1.040	1.460*	1.849*	0.707	1.326*	0.660	1.033*	1.293	0.812	**0.618**	0.126
	SITA	0.620*	1.425*	1.317*	1.601*	0.737*	1.394*	0.711*	1.448*	1.228*	1.007*	1.152*	0.562*
WCP	SS	**1.846***	**1.825***	1.820*	1.854*	1.877*	1.362*	**1.803***	1.652*	**1.552***	**1.810***	**1.747***	**1.768***
	SITA	2.016*	1.992*	1.669*	1.594*	1.483*	1.391*	1.772*	1.729*	1.686*	1.607*	1.781*	1.656*
SPH	SS	**1.963***	1.397*	1.625*	1.872*	1.717*	0.939	**1.482***	**1.271***	1.042*	1.551*	**1.937***	**2.015***
	SITA	2.194*	1.618*	1.550*	1.486*	1.127*	0.984*	1.447*	1.197*	1.209*	1.250*	1.886*	1.993*
WPH	SS	0.436	0.119	1.148	1.833*	1.271*	0.126	0.051	0.773*	0.937	1.030	**1.351***	0.877
	SITA	0.612*	0.707*	0.666*	1.414*	0.795*	− 0.012*	0.108*	0.923*	0.803*	0.658*	1.622*	1.039*
WHR	SS	− 2.102*	− 1.248	− 0.663	− 0.567	− 1.408	− 2.436*	0.499	1.220*	0.521	− **0.233**	− 1.320*	− 1.519*
	SITA	− 1.621*	− 0.470*	− 0.221*	0.150*	− 0.933*	− 2.248*	0.689*	1.072*	0.352*	− 0.032*	− 0.413*	− 0.434*
LGP	SS	− 1.945*	− 0.450	− 0.247	− 1.234	− 1.679*	0.300	1.453*	**1.586***	1.281*	**1.157***	0.905*	− 1.017*
	SITA	− 2.434*	− 0.087*	− 0.710*	− 1.180*	− 1.698*	0.015*	1.213*	1.365*	1.027*	0.767*	0.679*	− 0.960*
EHR	SS	1.008	1.474	1.048	− 0.805	0.612	1.644*	1.706*	**1.920***	1.467*	2.296*	**2.687***	**1.756***
	SITA	0.839*	1.756*	0.168*	− 0.884*	0.515*	1.398*	1.461*	1.628*	1.515*	2.061*	2.396*	1.900*

Table 1. Results of MK/m-MK and ITA analysis of maximum temperature for ACZ's of India. SS : Sen's Slope, SITA : Slope of ITA. *Significant at 5%; Bold font in SS indicates auto correlated data where m-MK is used.

ACZ	Parameter	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
EPH	SS	− 0.381	− 0.102	0.210	− 0.563	− 1.360*	− 1.168*	− 0.015	**− 0.098**	**0.119**	0.047	**1.600**	0.618
	SITA	− 0.952*	− 0.123*	0.232*	− 0.651*	− 1.106*	− 0.919*	− 0.017*	− 0.114*	0.076*	− 0.033*	1.193*	0.135*
MGP	SS	− 0.577	0.743	**0.691**	− 0.378	**− 1.234**	− 0.801	0.237	**0.189**	**0.312**	0.328	**1.269**	0.840
	SITA	− 0.789*	1.101*	0.751*	− 0.464*	− 0.820*	− 0.526*	0.294*	0.112*	0.269*	0.151*	1.149*	0.644*
TGP	SS	1.520*	1.951*	1.601*	1.346	1.144	− 0.961	0.582*	**1.104***	**1.100***	1.632*	2.554*	1.611*
	SITA	1.975*	2.592*	1.870*	1.388*	1.560*	− 0.552*	1.292*	1.266*	1.521*	1.691*	2.626*	1.993*
UGP	SS	0.246	1.315	**0.897**	0.517	− 0.423	− 1.314*	0.296	**0.722***	**1.041***	1.075*	2.060*	1.192*
	SITA	0.423*	1.951*	1.438*	0.500*	0.136*	− 0.968*	0.732*	0.942*	1.206*	1.021*	1.947*	1.410*
WDR	SS	1.287*	2.358*	**2.157***	2.387*	1.937*	0.538	1.017*	0.789*	**1.264***	1.897*	2.377*	1.254*
	SITA	1.848*	2.925*	2.467*	1.860*	2.161*	0.832*	1.238*	1.059*	1.483*	1.755*	2.331*	1.785*
CPH	SS	0.439	1.438	1.218*	1.165	0.548	− 0.621	0.373	**0.516**	**0.991***	1.760*	2.520*	1.150
	SITA	0.562*	1.934*	1.595*	0.977*	0.819*	− 0.352*	0.642*	0.760*	1.197*	1.556*	2.434*	1.226*
ECP	SS	0.558	0.195	0.751*	0.182	**− 0.133**	− 0.024	**0.500***	0.351*	**0.457***	0.435	1.376*	0.960
	SITA	0.508*	0.237*	0.825*	0.182*	− 0.141*	0.077*	0.528*	0.336*	0.451*	0.508*	1.288*	0.755*
GPH	SS	1.055	1.862*	1.627*	1.761*	**1.317***	**0.847***	0.837*	0.700*	**1.244***	1.789*	1.714*	0.988
	SITA	1.320*	2.336*	1.803*	1.372*	1.507*	1.101*	0.963*	0.983*	1.444*	1.649*	1.578*	1.112*
WCP	SS	**0.097**	0.185	0.291	0.214	0.426	0.621*	**0.794***	**0.624***	**0.694***	0.488*	0.949	0.569
	SITA	0.321*	0.075*	0.192*	0.177*	0.507*	0.795*	0.851*	0.854*	0.860*	0.578*	1.171*	0.355*
SPH	SS	0.451	− 0.099	0.340	0.157	0.221	0.291	**0.617***	**0.533***	**0.528***	0.324	1.217	0.581
	SITA	0.277*	− 0.337*	0.327*	0.045*	0.180*	0.475*	0.738*	0.649*	0.670*	0.377*	1.150*	0.345*
WPH	SS	− 0.122	0.218	0.020	− 0.127	0.232	0.098	0.308	0.318	0.634*	0.550	1.647	0.475
	SITA	− 0.049*	0.246*	0.016*	− 0.302*	0.242*	0.199*	0.425*	0.509*	0.671*	0.510*	1.601*	0.137*
WHR	SS	− 1.176*	**− 0.643**	− 0.943	− 1.257	− 1.205	− 2.126*	**0.141**	**0.250**	**− 0.256**	**− 0.682**	0.121	− 0.916
	SITA	− 0.519*	0.250*	− 0.338*	− 1.028*	− 0.615*	− 1.734*	0.395*	0.268*	0.294*	− 0.413*	0.478*	− 0.108*
LGP	SS	− 0.506	0.791	1.310*	0.287	**− 0.604**	**0.677**	1.054	**0.962**	**1.004**	**0.754**	**1.458***	0.938
	SITA	− − 0.576*	1.607*	1.679*	0.636*	0.080*	0.742*	1.240*	1.049*	1.029*	1.055*	1.869*	1.410*
EHR	SS	0.287	0.306	0.615	0.059	**0.266**	**0.825***	**0.920***	**0.895***	**0.879***	0.752	0.600	0.896*
	SITA	0.488*	1.081*	0.824*	0.147*	0.673*	0.981*	1.040*	0.933*	0.944*	1.010*	1.027*	1.334*

Table 2. Results of MK/m-MK and ITA analysis of minimum temperature for ACZ's of India. *SS* : Sen's Slope, *SITA*: Slope of ITA. *Significant at 5%; Bold font in SS indicates auto correlated data where m-MK is used.

discernible trend. WHR and LGP are the regions that demonstrate a predominantly declining trend, with all the methods showing a significant decreasing trend during specific months. For WHR, MK/m-MK highlights a significant decline in January, June, November, and December, while August shows a significantly increasing trend. Similarly, ITA indicates a significant increase in April and from July to September, while the rest of the month indicates a significantly decreasing trend. Moreover, under IPTA, January, May, and June show a decreasing trend, while July to September shows an increasing trend. LGP exhibits a significant decreasing trend for January, May, and December under the MK/m-MK method, while IPTA detects a decreasing trend for January, March to May. Similarly, ITA reveals a decreasing trend from January to May and December. However, a significant increase was observed from July to November under MK/m-MK and June to November using both ITA and IPTA methods, respectively. In the context of EHR, MK/m-MK reveals a significantly increasing trend from June to December. In contrast, ITA and IPTA indicated an increasing trend across all the months except April, which exhibits a significantly decreasing trend.

In summary, during January, MK/m-MK showed significant decreasing trends in five ACZs and significantly increasing trends in three ACZs of India, while the ITA and IPTA showed significant trends in all ACZs, among which eight were increasing and six were decreasing. August was identified as a month of significantly increasing trend under MK/m-MK, while under both ITA and IPTA methods, August and September were identified as the same. Out of the fourteen zones examined, four specific zones, namely ECP, GPH, WCP, and SPH, were identified as exhibiting only increasing trends. Conversely, the remaining ten zones display one or more months with significant decreasing trends.

Minimum temperature
The analysis reveals a disparity between maximum and minimum temperature time series regarding a significant decreasing trend across the zone and method. A lower frequency of significant decreasing trend is observed in the minimum temperature time series compared to the maximum. Moreover, the ITA method consistently detected significant trends across all the 168-time series tested, indicating its robustness in trend identification. At the same time, the MK/m-MK and IPTA could detect trends in 38.7% and 85.7% time series, respectively. Furthermore, EPH, MGP, and WHR zones were identified as the highest number in the months, with a significant declining trend. Conversely, WDR, GPH, WCP, and EHR zones were characterized by the absence of significant declines.

Under the MK/m-MK method, the May and June months had significantly declining trends over EPH, while the ITA method exhibits the maximum number of significantly declining months except March, September, November, and December, demonstrating significantly increasing trends. Similarly, using the IPTA method, January, April to June had a declining trend, while March, November, and December had an increasing trend. Over MGP solely, ITA and IPTA identify significant trends. As per ITA and IPTA, January and April to June exhibit a decreasing trend, while the remaining months had an increasing trend under ITA. Meanwhile, under IPTA, July, August, and October show no discernible trends. In the case of the TGP, the MK/m-MK method delineates a pattern of significant increasing trends, except from April to June, which displays no discernible trend.

In contrast, the ITA and IPTA method identifies a significantly increasing trend for all the months except June, where a significantly decreasing trend was observed. Similarly, using the MK/m-MK method, a significant increase in the trend was observed in UGP from August to December. In contrast, the ITA indicates a consistent, significant increasing trend across all months, except for June, where both methods depict a significantly decreasing trend. ITPA exhibits the same behavior as ITA, except for May, which shows no trend. WDR had the sharpest significant increasing trend of 2.925 °C/100 year during February. Across all the months, all three methods detected an increasing trend in WDR, except for June, where the MK/m-MK method detected no significant trend. ITA and ITPA methods for ECP and CPH zones depicted significantly decreasing trends for May and June, respectively, while the rest of the month had significantly increasing trends under every method except for June over ECP, which shows no trend. On the other hand, the MK/m-MK method shows a significantly increasing trend for certain months. In the case of GPH, all the methods detect significant increasing trends except for January and December under MK/m-MK, where no significant trend was observed. Within the WCP zone, the ITA method reveals a significant increase across all months. Like ITA, the IPTA shows the same except for February, which reveals no trend. In contrast, the MK/m-MK method identifies a significantly increasing trend only for June and October. Similarly, in the SPH zone, the ITA and IPTA method identifies February as a significantly decreasing trend month, while the rest of the month depicts a significantly increasing trend, except April under IPTA, which identifies no trend. The MK/m-MK method indicated a significantly increasing trend from July to September. For WPH, a significant negative trend was observed for January and April under ITA, while using the IPTA, only February and May to November months were observed to have an increasing temperature trend.

On the other hand, MK/m-MK captures a significant increase in trend only for September. WHR zone exhibits a significant decreasing trend for January and June under the MK/m-MK method, where June recorded the sharpest significant decline of − 2.126 °C/100 year, while ITA identifies a significant decreasing trend from January, March to June, October, and December with the remaining months showing significantly increasing trends. At the same time, IPTA identifies January, April, May, June, and October as decreasing trend months and November as an increasing trend month. Again, in LGP, January was recognized as a significantly decreasing month under ITA and IPTA methods, while the rest of the month shows vice-versa except for May, where no discernible trends were observed. However, the MK/m-MK method only detects a significantly increasing trend in March and November. Lastly, in the EHR zone, ITA and IPTA showed significantly increasing trends across all months, while MK/m-MK identified significantly increasing trends only from June to September and in

Fig. 2. (**a**) Results of monthly trend analysis of maximum temperature using ITA for the period 1951–2022. (**b**) Results of monthly trend analysis of maximum temperature using ITA for the period 1951–2022.

First half of the series
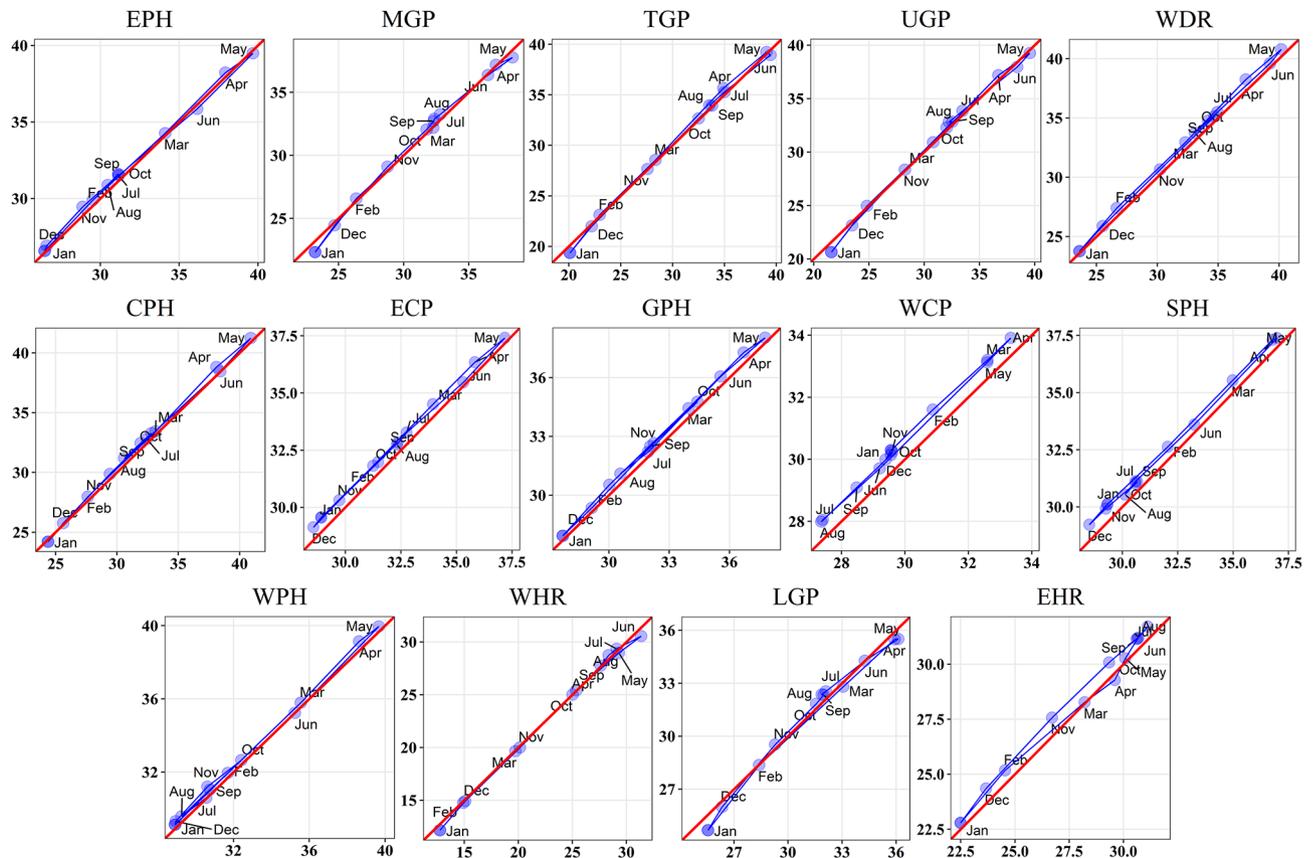
Fig. 2. (continued)

Fig. 3. Results of monthly trend analysis of maximum temperature using IPTA for the period 1951–2022.

December. The comparison underscores the disparity in trend identification between the three methods and provides insights into the spatio-temporal dynamics between different ACZs of India.

Diurnal temperature range (DTR)
The trends in DTR of all ACZs were significant at a 5% significance level as analyzed by the ITA method. The EPH, ECP, WCP, and SPH have consistently increasing trends of DTR and the magnitude of this increase is higher in winter months (JF) than the rest of the year. The SITA of DTR ranged from 0.113 to 1.452, 0.332–1.346, 0.595–1.917, and 0.509–1.955 °C/100 year in EPH, ECP, WCP and SPH, respectively. The WPH and EHR also had increasing DTR in most of the months. The TGP, UGP, LGP, WDR, and GPH had decreasing trends of DTR in most of the months, especially the post-monsoon (OND) and winter months (JF). The highest decrease of -4.067 °C/100 year was observed in January of the TGP, while the highest increase of 1.955 °C/100 year was observed in SPH in February (Fig. 10).

Comparison of trend analysis methods

Combining the maximum and minimum temperature time series, 336 temperature time series were examined using MK/m-MK, ITA and IPTA. The comparative analysis of trend test results is provided in Fig. 11. Using the traditional MK/m-M-MK test, trends were significant in 44.6% of temperature time series data tested, while the graphical IPTA showed that the trends were significant in 86% of time-series data. The ITA method successfully identified significant trends across all analyzed time-series data, suggesting its efficacy in detecting numerous trends that conventional methods like MK/m-MK and the IPTA test may overlook. Moreover, ITA demonstrated its capability to detect all significant trends detectable by MK/m-MK and the IPTA test. However, the monthly transitions, as depicted by the IPTA plots, provide considerable information on seasonal temperature variations across ACZs of India.

As there are no similar studies in India on the same spatio-temporal scale using the MK, ITA and IPTA methods, we compared our findings with similar research performed on different spatio-temporal scales and data but similar methodology in India and different parts of the world to compare our outcomes of different methods and the trends of temperature. Acar[40] compared the traditional MK with ITA and IPTA for both temperature and rainfall station data of the Upper Euphrates Basin of Turkey and reported similar findings of getting more significant trends using the ITA and IPTA methods compared to the traditional MK test. Esit et al.[25] also reported similar findings of getting hidden trends in the hydro-meteorological variables by utilizing the ITA and IPTA methodologies. They reported that ITA, IPTA and MK captured 86, 75 and 22% significant temperature trends in Ankara, Turkey. Şan et al.[41] also reported the highest trend detection using the ITA (93%),
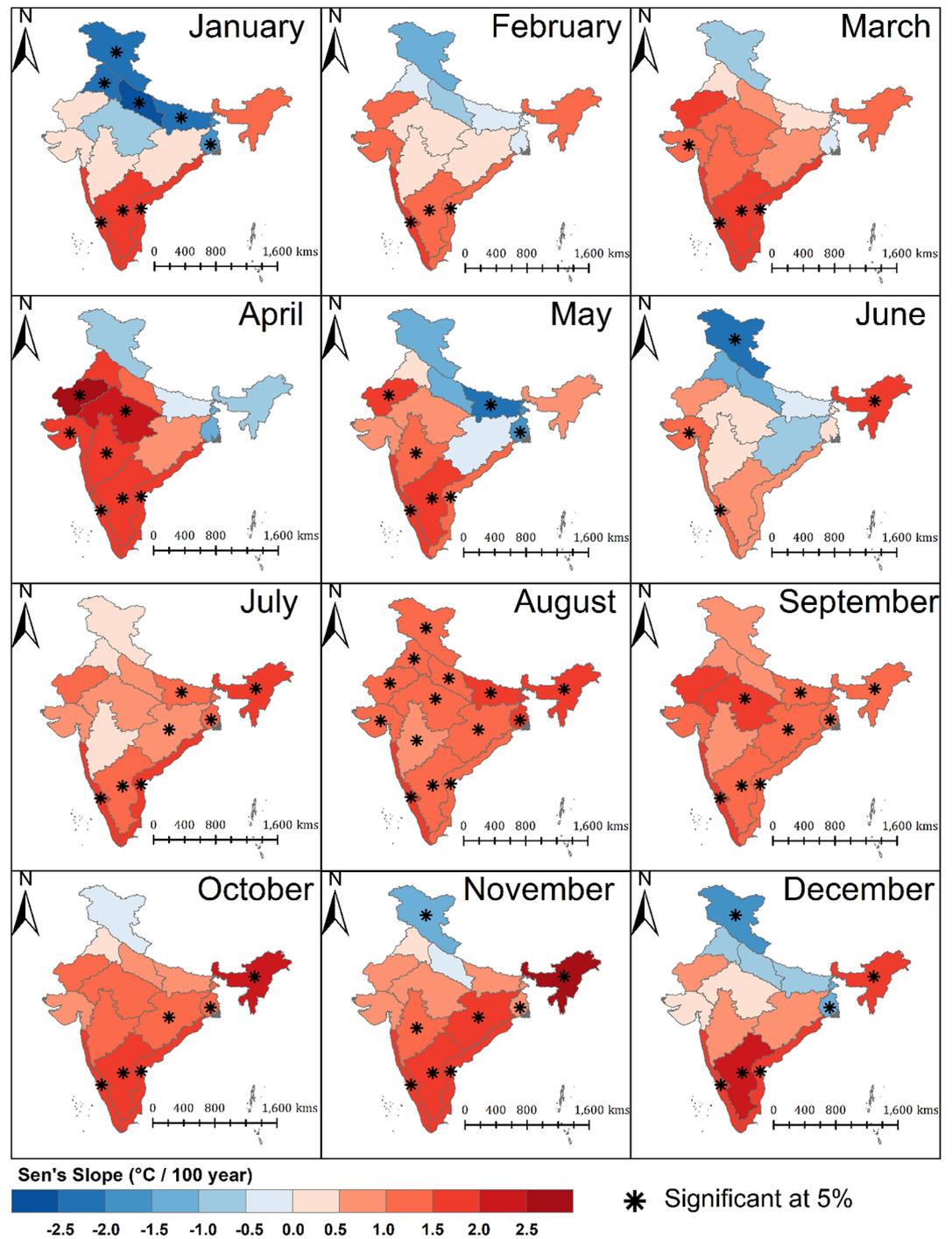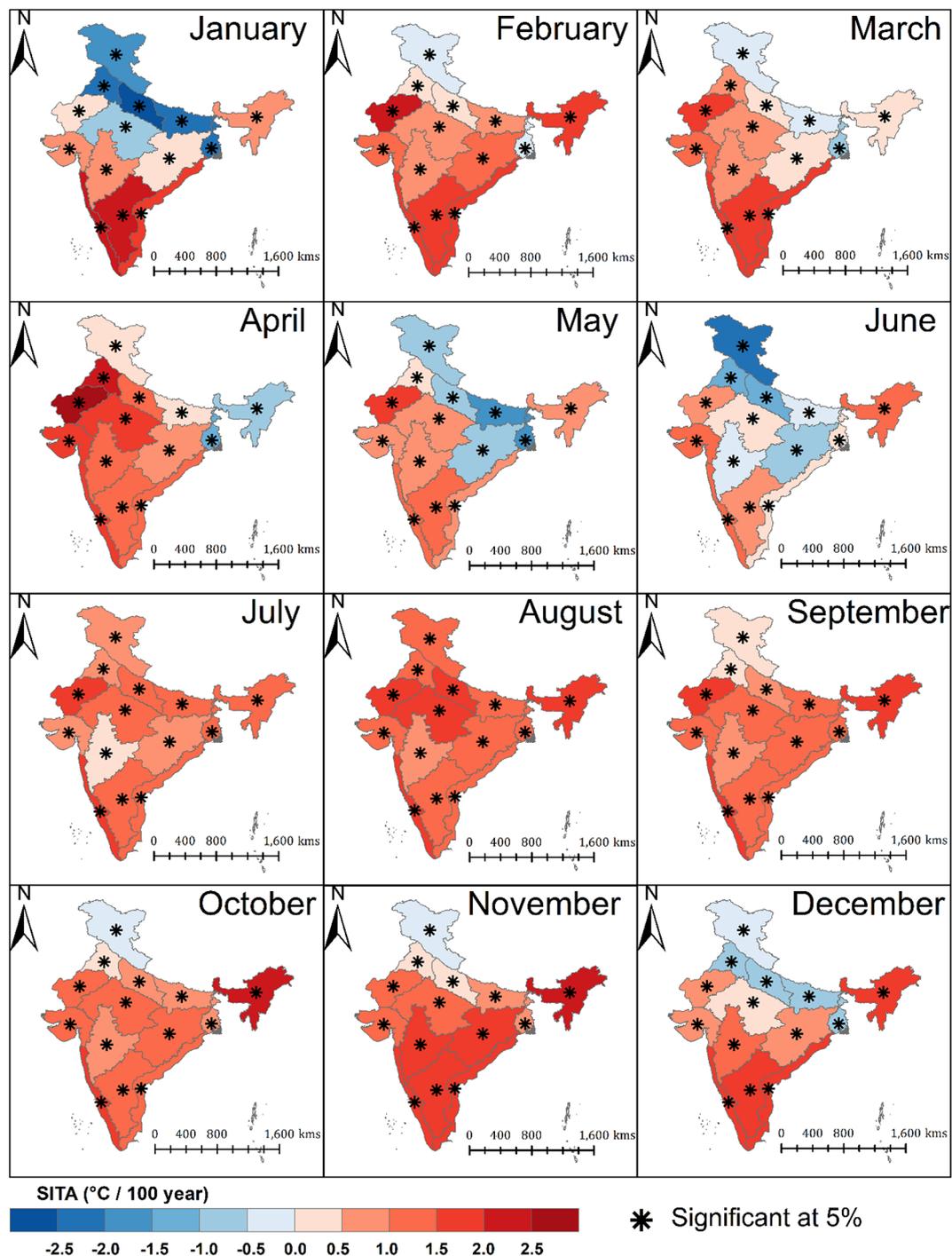
Fig. 4. Spatial variations in trends of maximum temperature using Sen' slope during 1951–2022. Created by ArcGIS Desktop v 9.1. https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview.

followed by IPTA (88%) and MK (26%) methods for monthly rainfall data of Vu Gia-Thu Bon River Basin of Vietnam. Our results on the sensitivity of the methods in detecting trends were also supported by other researchers also[42–45].

Though the ITA detected a higher number of significant trends, the MK test results align closely with the ITA findings in terms of both trend direction and magnitude. It is also important to acknowledge the inherent uncertainties in these approaches. To address the potential impact of serial correlation on the MK test, we applied the modified MK test, which adjusts for autocorrelation and thus provides results that are more reliable[46]. The ITA offers greater sensitivity, and it may result in the over-detection of trends that are not statistically significant and at the same time, IPTA, despite its comprehensive nature, can present interpretation challenges when variables show conflicting trends. Hence, for practical decision-making, it is advisable to cross-validate the trends

Fig. 5. Spatial variations in trends of maximum temperature using slope of ITA during 1951–2022. Created by ArcGIS Desktop v 9.1. https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview.

detected by these methods, particularly focusing on those consistently identified across different methods. This reduces the potential for over-detection while still capturing critical changes, ensuring the decisions are based on the most reliable, statistically robust and consistent trend results.

The trends of maximum and minimum temperature obtained in our work is also supported by several findings. Nengzouzam et al.[47] used only the MK test for gridded points for 1696–2005 over India, without averaging the data for any particular geographical boundary as it was done for ACZ of India. They reported that the maximum temperature showed notable declining trends across the entire Indo-Gangetic plains extending up to the Northeast parts of the country, whereas the Southern parts experienced rising temperatures. Every region except the Central part exhibited rising trends for minimum temperature, signifying warming. Apart from the trend direction, the SS values are on the lower side as compared to our work, which may be due to

Fig. 6. (**a**). Results of monthly trend analysis of minimum temperature using ITA for the period 1951–2022. (**b**). Results of monthly trend analysis of minimum temperature using ITA for the period 1951–2022.

Fig. 6. (continued)
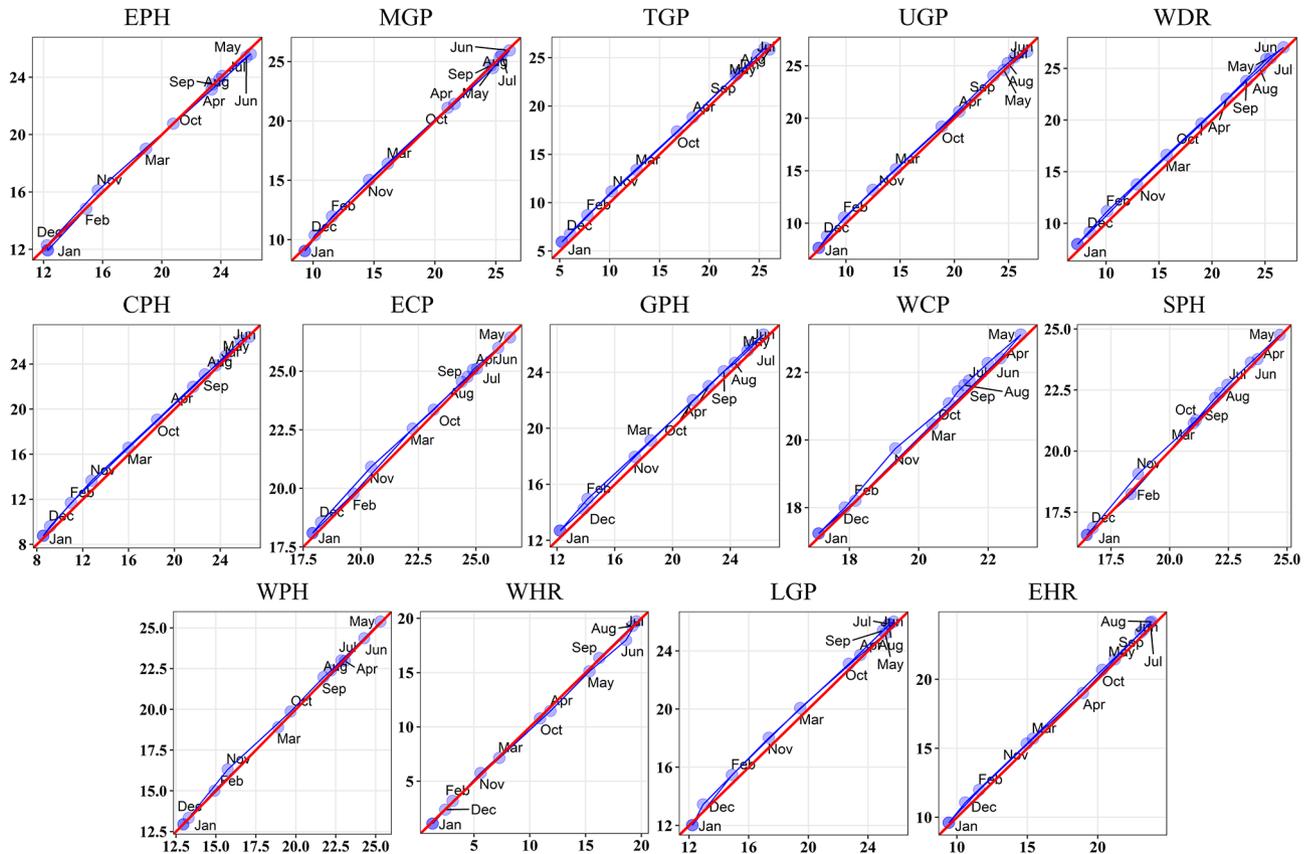
Fig. 7. Results of IPTA of minimum temperature for the period 1951–2022.

the higher rate of changes in temperature due to climate change in recent decades[48]. Rao et al.[49] using MK test, showed increasing temperature trends in most parts of India for annual temperature, which aligns with most of the months we tested. The findings of Ross et al.[50] also validate our findings of getting consistent heating in the southern, central and western ACZs and some cooling areas in the northern ACZs during winter, which may be attributed to the haziness caused by the aerosols that reduce the solar radiation leading to a cooling effect[51]. The literature on small-scale temperature studies in different parts of India also supports our findings. For example, Jain et al.[52] found that the maximum and minimum temperature over northeast India is significantly increasing, which overlaps with the EHR ACZ of our work, particularly in the second half of the year using MK and SS. Singh et al.[8] reported significantly increasing temperatures in Maharashtra, which is mostly the WHP part of our study, with a similar magnitude of trend using the MK test. Machiwal et al.[53] observed notable upward trends in the WDR from 1979 to 2013 through MK and SS tests. Pingale et al.[54] noted significant temperature rises across most areas of Rajasthan (WDR), examining minimum, maximum, and average temperatures with MK and SS tests. Radhakrishnan et al.[55] also demonstrated rising temperature trends in India from 1985 to 2014, employing MK, SS, and SLR tests. Additionally, Meshram et al.[56] in their work on annual and seasonal temperatures of Chhattisgarh (part of EPH), reported rising temperature trends for the period 1901–2000 using MK and SS in their analysis. Jhajharia et al.[57] also analyzed the trends of maximum and minimum temperatures in the Godavari Basin using the MK test. They observed increasing trends in maximum temperature during December and the post-monsoon season and rising minimum temperatures in July, September, and throughout the monsoon season. A notable observation pertains to the trend magnitude, where comparisons with SS values from previous studies suggest our findings trend slightly higher, underscoring the accelerated rate of temperature change witnessed in recent decades. In neighboring countries and regions, researchers have also reported similar findings with similar. For example, in Bangladesh, Khan et al.[58] reported increasing trends in both maximum and minimum temperatures using the MK test for 1988–2017. In Iran, Ahmadi et al.[12] reported increasing average annual temperature trends during autumn, spring and summer seasons of 1961–2010 using the MK test. For Pakistan, recently, Hussain et al.[59] reported rising seasonal and annual Tmin, Tmax, Tmean, and DTR across most regions of the country for the period 1961–2017 using MK and SS tests.

In most parts of the country, consistent increase in minimum temperature, trends were observed. Researchers have well documented the increase in minimum night temperatures as a concern for most of the *rabi* crops, which require cool climates for growth and development. The increasing minimum temperatures coinciding with the flowering and grain filling stage of the crops affect the quality and reduces the yield of crops like wheat[60], rice[61], maize[62] etc. The Western and Southern parts consistently show increasing maximum temperature trends in almost all months, indicating increasing exposure to high daytime temperatures, which will negatively impact
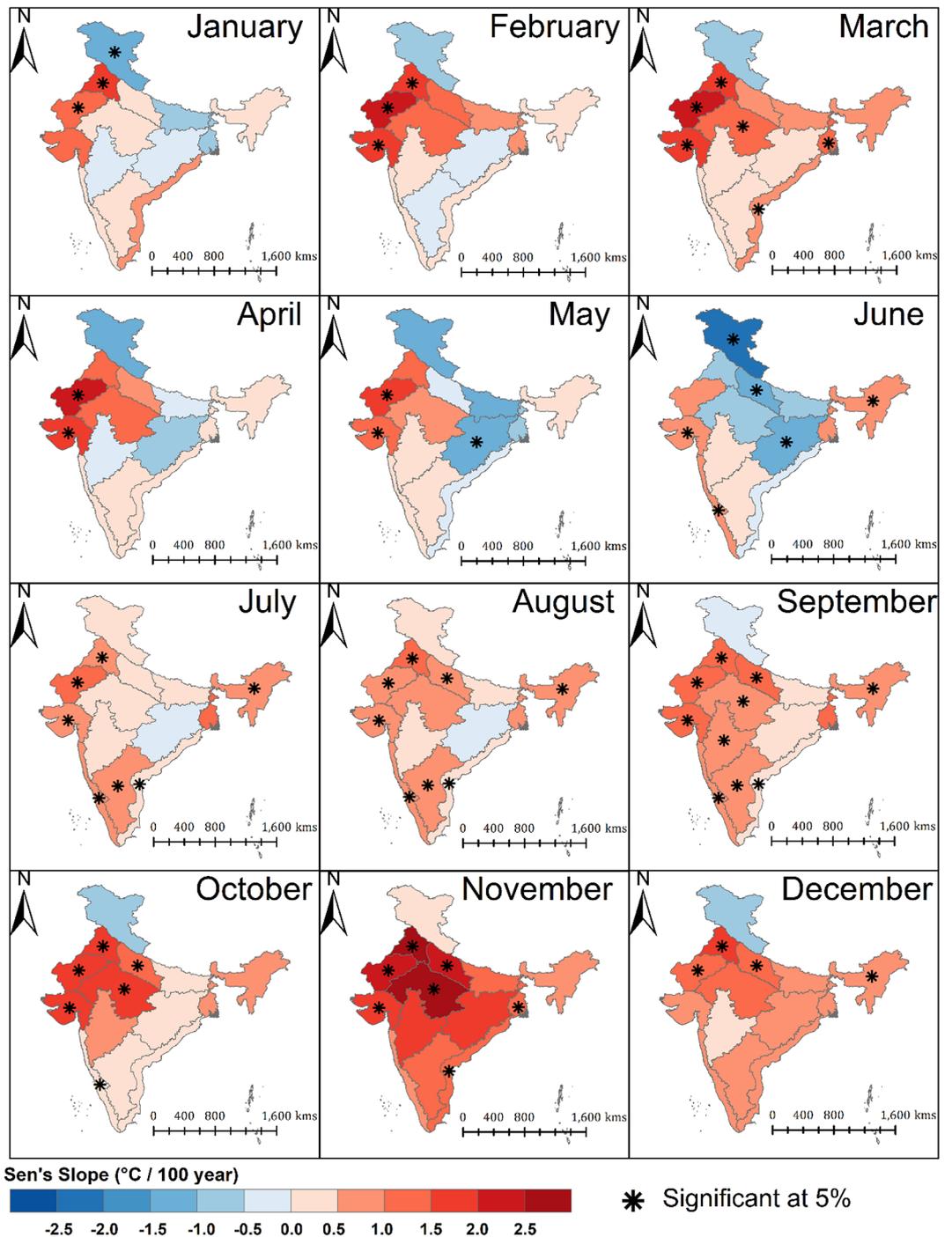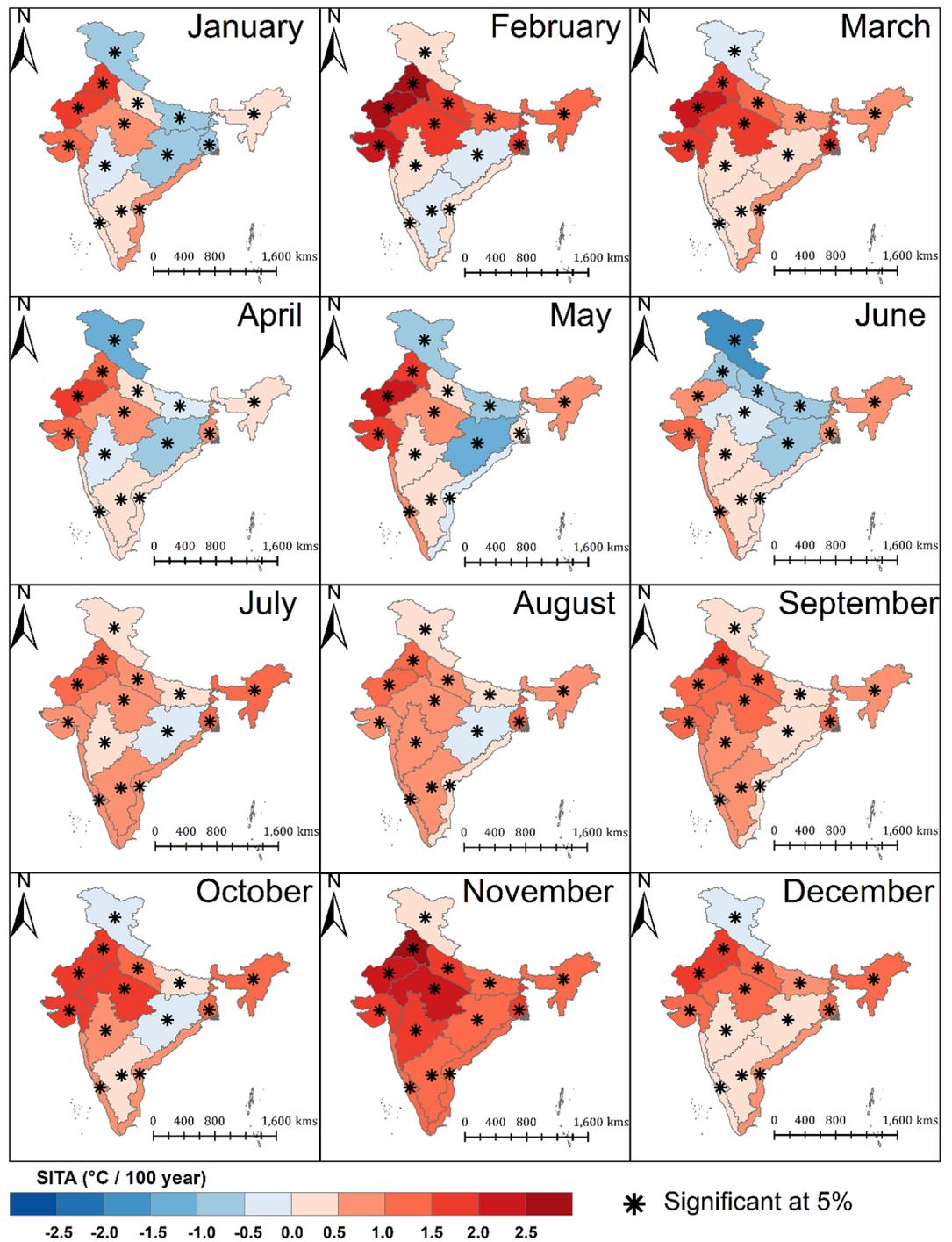
Fig. 8. Spatial variations in trends of minimum temperature using Sen' slope during 1951–2022. Created by ArcGIS Desktop v 9.1. https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview.

the yield of agricultural crops like wheat[63], rice[63], maize[63] and soybean[63]. The major part of the monsoon season of the whole country (July, August and September) has an increasing exposure to high daytime temperatures, which may negatively impact the growth and development of *kharif* crops grown in the whole country. The increasing daytime maximum temperatures affect the growing season, quality and yield of crops by affecting the pollen viability, photosynthesis, and transpiration rate[62]. The rising daytime temperatures cause brief heat spikes, affecting crop yields across different ACZs[64]. The increasing temperatures are also known to negatively impact fruits, vegetables and plantation crops grown in India[65]. Zhao et al.[63] reported a 6%, 3.2%, 7.4% and 3.1% decline in wheat, rice, maize and soybean yield with each degree rise in temperature. The regions with sustained warming (due to increasing minimum and maximum temperatures) may stress crops at various growth and developmental stages, potentially affecting the entire growing season[66]. The DTR trends showed that the northern and western parts of the country have declining trends from October to March, indicating the

Fig. 9. Spatial variations in trends of minimum temperature using slope of ITA during 1951–2022. Created by ArcGIS Desktop v 9.1. https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview.

narrowing range of temperature in the region, while the central and the southern parts have increasing trends of DTR, indicating more extremes in the region due to asymmetry of maximum and minimum temperature trends. To address these impacts of temperature variability on crops, the key adaptation strategy would be the development of tolerant varieties to high and low-temperature stresses, shifting the planting dates to avoid the critical crop growth stages coinciding with stressed conditions, efficient water management practices, protective cultivation of crops and crop insurance[67]. At the same time, a multifaceted approach that includes sustainable agricultural practices, agroforestry, climate-smart agriculture, and strong policy support is essential to mitigate the impacts[68]. However, the response of individual crops to these changes will vary significantly, necessitating crop and region-specific future studies assessing the impacts and suggesting ACZ and crop-specific adaptation and mitigation measures. Additionally, the effects of short-term and long-term persistence on the trends should
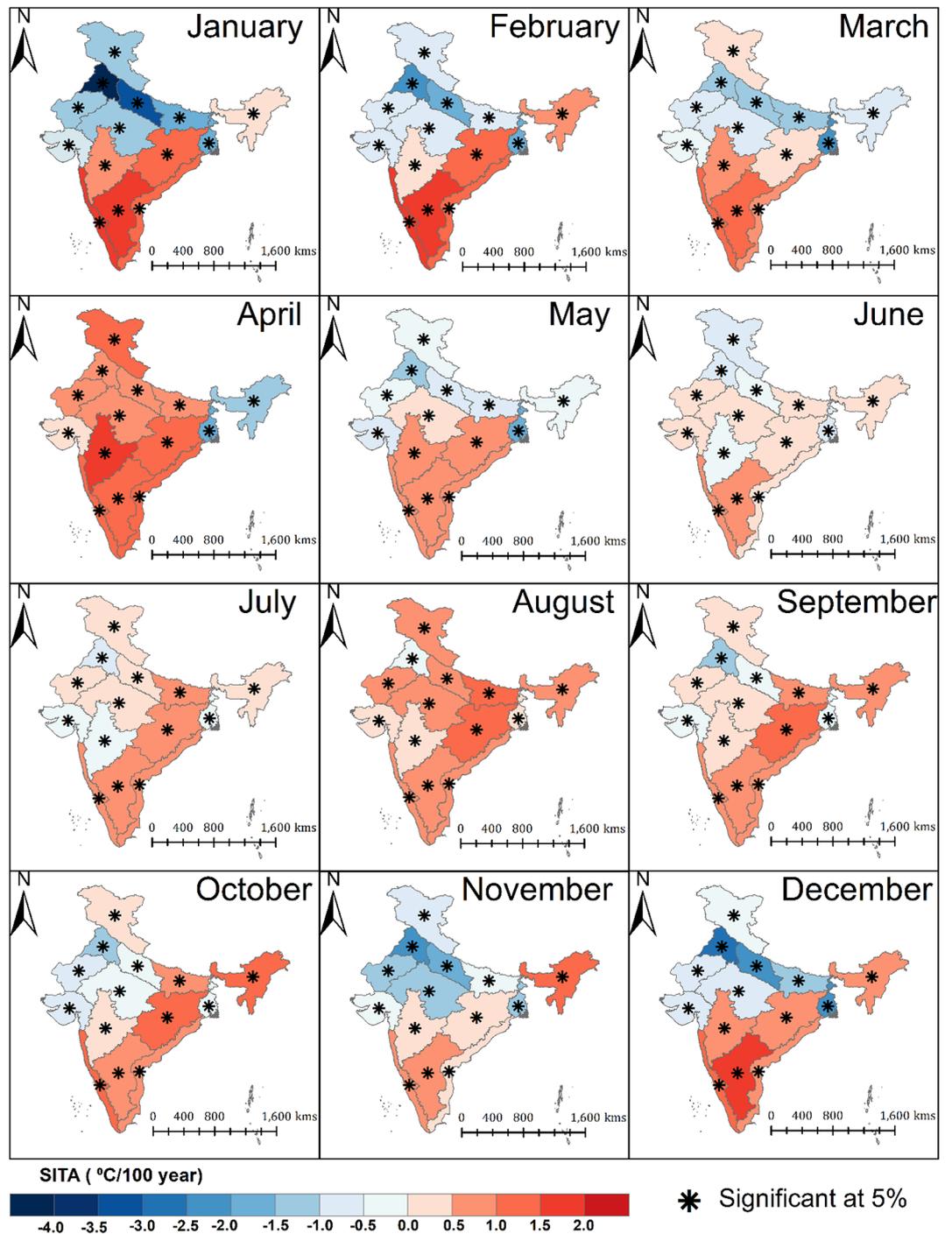
Fig. 10. Spatial variations in trends of DTR using slope of ITA during 1951–2022.
Created by ArcGIS Desktop v 9.1. https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview.

be analyzed to get better insights[69]. The regional variability observed in the trends could be influenced by factors such as topography, land use, and regional climate patterns. Future studies could explore these factors in more detail to inform region-specific climate resilience strategies.

Conclusions

This study utilized innovative graphical methodologies alongside the traditional MK/m-MK method to analyze and compare the trends in monthly maximum and minimum temperatures from 1951 to 2022 (72 years). By integrating polygonal and innovative techniques, a thorough examination of long-term climatic shifts within various ACZs of India was achieved, furnishing a comprehensive understanding of long-term climate changes. The MK/m-MMK and IPTA tests captured significant trends in 44.6% and 86% of the time series
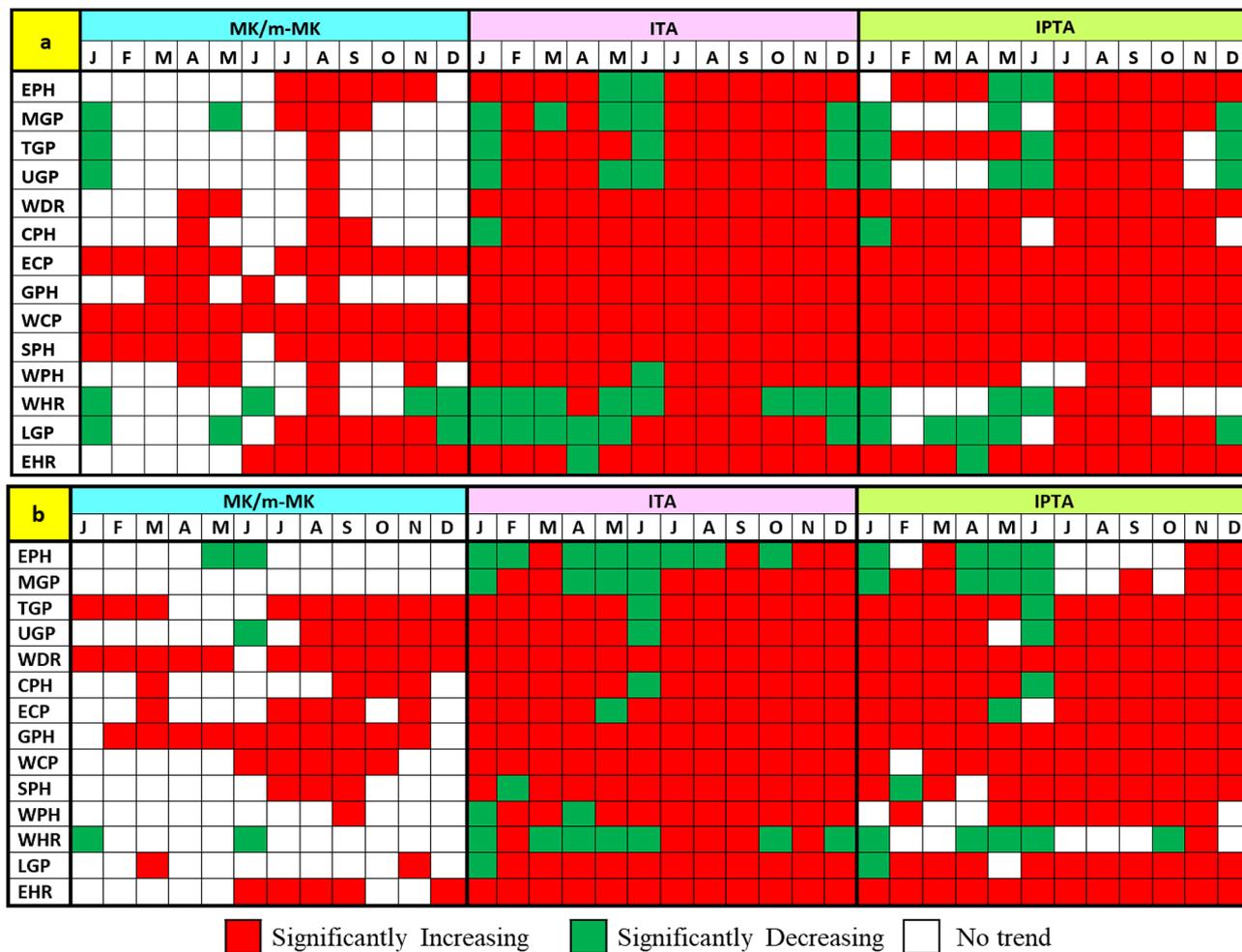
Fig. 11. Comparison of trend detection methodologies for (**a**) maximum and (**b**) minimum temperature.

data, respectively. Interestingly, the ITA method identified significant trends in all tested time series, indicating its superior ability to capture trends compared to MK/m-MMK and IPTA tests. For practical applications, we recommend considering trends that are detected by all methods for effective and reliable decision-making to mitigate the risk of over-detection associated with ITA. India's southern, western, and central regions exhibit consistently increasing trends in monthly maximum and minimum temperatures. The WDR, CPH, ECP, GPH, WCP, SPH, WPH, and EHR have mostly increasing trends in both maximum and minimum temperatures. The Gangetic plains (TGP, UGP, MGP and LGP) showed decreasing trends of maximum temperature in January, February, May and June. The DTR has increasing trends in the northern and western parts, while it has increasing trends in the central and southern parts of the country. Our findings underscore the significance of employing advanced analytical techniques, enabling a more nuanced understanding of long-term temperature trends, which is essential for formulating climate resilience strategies and adaptation measures in the face of ongoing climate change.

Data availability
Data supporting the findings of this study are available from the corresponding author on reasonable request.

References
1. WMO. Climate change indicators reached record levels in 2023. *Climate change indicators reached record levels in 2023*. https://wmo.int/news/media-centre/climate-change-indicators-reached-record-levels-2023-wm (2024).
2. WFP. A global food crisis. *A global food crisis*. scale of the current,next meal is coming from https://www.wfp.org/global-hunger-crisis#:~:text=The (2024).
3. Nagamani, K., Mishra, A. K., Meer, M. S. & Anuradha, B. Mapping severe tropical cyclone tauktae across the Arabian Sea and Western Coast of India using remote sensing and machine learning during May 2021. In *International Conference on Data Science, Agents & Artificial Intelligence (ICDSAAI)* 1–5. https://doi.org/10.1109/ICDSAAI59313.2023.10452623 (IEEE, 2023).

4. Nagamani, K., Mishra, A. K., Meer, M. S. & Das, J. Understanding flash flooding in the Himalayan Region: a case study. *Sci. Rep.* **14**, 7060 (2024).
5. Nagamani, K., Meer, M. S., Mishra, A. K., Sheriff, M. R. & Najar, M. A. Application of Satellite and geospatial technology for flash flood mapping over himalayan with reference to Dharamshala in Himachal Pradesh, India during July 2021. *J. Appl. Nat. Sci.* **16**, 534–542 (2024).
6. Sah, S., Singh, R. N., Chaturvedi, G. & Das, B. Trends, variability, and teleconnections of long-term rainfall in the Terai region of India. *Theor. Appl. Climatol.* https://doi.org/10.1007/s00704-020-03421-y (2020).
7. Singh, R. N., Sah, S., Das, B., Vishnoi, L. & Pathak, H. Spatio-temporal trends and variability of rainfall in Maharashtra, India: analysis of 118 years. *Theor. Appl. Climatol.* https://doi.org/10.1007/s00704-020-03452-5 (2020).
8. Singh, R. N. et al. Long-term spatiotemporal trends of temperature associated with sugarcane in west India. *Arab. J. Geosci.* **14**, 1–17 (2021).
9. Agbo, E. P., Nkajoe, U. & Edet, C. O. Comparison of Mann–Kendall and Şen's innovative trend method for climatic parameters over Nigeria's climatic zones. *Clim. Dyn.* **60**, 3385–3401 (2023).
10. Vani, P. C., Sahoo, B. C., Paul, J. C., Sahu, A. P. & Mohapatra, A. K. B. Trend analysis in gridded rainfall data using Mann–Kendall and Spearman's rho tests in Kesinga Catchment of Mahanadi River Basin, India. *Pure Appl. Geophys.* **180**, 4339–4353 (2023).
11. Kliengchuay, W. et al. Analyzing temperature, humidity, and precipitation trends in six regions of Thailand using innovative trend analysis. *Sci. Rep.* **14**, 7800 (2024).
12. Ahmadi, F., Nazeri Tahroudi, M., Mirabbasi, R., Khalili, K. & Jhajharia, D. Spatiotemporal trend and abrupt change analysis of temperature in Iran. *Meteorol. Appl.* **25**, 314–321 (2018).
13. Dinpashoh, Y., Jhajharia, D., Fakheri-Fard, A., Singh, V. P. & Kahya, E. Trends in reference crop evapotranspiration over Iran. *J. Hydrol.* **399**, 422–433 (2011).
14. Yue, S., Pilon, P., Phinney, B. & Cavadias, G. The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrol. Process.* **16**, 1807–1829 (2002).
15. Şen, Z. Innovative trend analysis methodology. *J. Hydrol. Eng.* **17**, 1042–1046 (2012).
16. Wu, H. & Qian, H. Innovative trend analysis of annual and seasonal rainfall and extreme values in Shaanxi, China, since the 1950s. *Int. J. Climatol.* **37**, 2582–2592 (2017).
17. Caloiero, T. Evaluation of rainfall trends in the South Island of New Zealand through the innovative trend analysis (ITA). *Theor. Appl. Climatol.* **139**, 493–504 (2020).
18. Singh, R. N. et al. Innovative trend analysis of spatio-temporal variations of rainfall in India during 1901–2019. *Theor. Appl. Climatol.* **145**, 821–838 (2021).
19. Birpınar, M. E., Kızılöz, B. & Şişman, E. Classic trend analysis methods' paradoxical results and innovative trend analysis methodology with percentile ranges. *Theor. Appl. Climatol.* **153**, 1–18 (2023).
20. Niazkar, M. et al. Drought analysis using innovative trend analysis and machine learning models for Eastern Black Sea Basin. *Theor. Appl. Climatol.* **155**, 1605–1624 (2024).
21. Şen, Z., Şişman, E. & Dabanli, I. Innovative polygon trend analysis (IPTA) and applications. *J. Hydrol.* **575**, 202–210 (2019).
22. Sezen, C. A new wavelet combined innovative polygon trend analysis (W-IPTA) approach for investigating the trends in the streamflow regime in the Konya Closed Basin, Turkey. *Theor. Appl. Climatol.* **151**, 1523–1565 (2023).
23. Gupta, N. & Chavan, S. R. Assessment of changes in monthly streamflow using innovative polygon trend analysis in the South Indian Rivers. *Arab. J. Geosci.* **16**, 657 (2023).
24. Koycegiz, C. & Buyukyildiz, M. Applications of innovative polygon trend analysis (IPTA) and trend polygon star concept (TPSC) methods for the variability of precipitation in Konya Closed Basin (Turkey). *Theor. Appl. Climatol* 1–16 (2023).
25. Esit, M., Yuce, M. I., Deger, İ. H. & Yasa, I. Trend and variability analysis in rainfall and temperature records over Van Province, Türkiye. *Theor. Appl. Climatol.* **155**, 451–472 (2024).
26. Machiwal, D. & Jha, M. K. Evaluating persistence and identifying trends and abrupt changes in monthly and annual rainfalls of a semi-arid region in Western India. *Theor. Appl. Climatol.* **128**, 689–708 (2017).
27. Singh, R. K. & Singh, D. N. An agroclimatic approach to agricultural development in India. In *Systems approaches for agricultural development: Proceedings of the International Symposium on Systems Approaches for Agricultural Development, 2–6 December 1991, Bangkok, Thailand* 111–125 (Springer, 1993).
28. Srivastava, A. K., Rajeevan, M. & Kshirsagar, S. R. Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region. *Atmos. Sci. Lett.* https://doi.org/10.1002/asl.232 (2009).
29. Jhajharia, D. & Singh, V. P. Trends in temperature, diurnal temperature range and sunshine duration in Northeast India. *Int. J. Climatol.* **31**, 1353–1367 (2011).
30. Mann, H. B. Non-parametric tests against trend. *Econometrica.* **13**, 245 (1945).
31. Kendall, M. G. *Rank Correlation Methods. 4* (Charles Griffin, 1975).
32. Novotny, E. V. & Stefan, H. G. Stream flow in Minnesota: Indicator of climate change. *J. Hydrol.* **334**, 319–333 (2007).
33. Hamed, K. H. & Ramachandra Rao, A. A modified Mann–Kendall trend test for autocorrelated data. *J. Hydrol.* **204**, 182–196 (1998).
34. Shahin, M., van Oorschot, H. J. L. & de Lange, S. J. *Statistical Analysis in Water Resources Engineering* (A.A. Balkema, 1993).
35. Haan, C. *Statistical Methods in Hydrology* (Iowa State University, 2002).
36. Chandniha, S. K., Meshram, S. G., Adamowski, J. F. & Meshram, C. Trend analysis of precipitation in Jharkhand State, India: investigating precipitation variability in Jharkhand State. *Theor. Appl. Climatol.* **130**, 261–274 (2017).
37. Sen, P. K. Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.* **63**, 1379–1389 (1968).
38. Theil, H. A rank-invariant method of linear and polynomial. *Mathematics.* **392**, 387–392 (1950).
39. Şen, Z. Innovative trend significance test and applications. *Theor. Appl. Climatol.* **127**, 939–947 (2017).
40. Acar, R. A comparison of the performance of different innovative trend assessment approaches for air temperature and precipitation data: an application to Elazığ Province (Turkey). *J. Water Clim. Chang.* jwc2024685 (2024).
41. Şan, M., Akçay, F., Linh, N. T. T., Kankal, M. & Pham, Q. B. Innovative and polygonal trend analyses applications for rainfall data in Vietnam. *Theor. Appl. Climatol.* **144**, 809–822 (2021).
42. Esit, M. Investigation of innovative trend approaches (ITA with significance test and IPTA) comparing to the classical trend method of monthly and annual hydro-meteorological variables: a case study of Ankara region, Turkey. *J. Water Clim. Chang.* **14**, 305–329 (2023).
43. Ahmed, N. et al. Innovative polygon trend analysis of monthly precipitation (1952–2015) in the Hindukush-Karakoram-Himalaya river basins of Pakistan. *Int. J. Climatol.* **42**, 9967–9993 (2022).
44. Hırca, T., Eryılmaz Türkkan, G. & Niazkar, M. Applications of innovative polygonal trend analyses to precipitation series of Eastern Black Sea Basin, Turkey. *Theor. Appl. Climatol.* **147**, 651–667 (2022).
45. Karacosta, P., Pakalidou, N., Douka, M. & Karacostas, T. Innovative Polygon Trend Analysis (IPTA): A Case Study for Precipitation in Thessaloniki during the Last 50 Years (1971–2020). *Environ. Sci. Proc.* **26**, 161 (2023).
46. Wang, W., Chen, Y., Becker, S. & Liu, B. Variance correction prewhitening method for trend detection in autocorrelated data. *J. Hydrol. Eng.* **20**, 4015033 (2015).
47. Nengzouzam, G., Hodam, S., Bandyopadhyay, A. & Bhadra, A. Spatial and temporal trends in high resolution gridded temperature data over India. *Asia-Pac. J. Atmos. Sci.* **55**, 761–772 (2019).

48. Calvin, K. et al. *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. https://www.ipcc.ch/report/ar6/syr/. https://doi.org/10.59327/IPCC/AR6-9789291691647 (2023).
49. Rao, B. B., Chowdary, P. S., Sandeep, V. M., Rao, V. U. M. & Venkateswarlu, B. Rising minimum temperature trends over India in recent decades: implications for agricultural production. *Glob. Planet. Change.* **117**, 1–8 (2014).
50. Ross, R. S., Krishnamurti, T. N., Pattnaik, S. & Pai, D. S. Decadal surface temperature trends in India based on a new high-resolution data set. *Sci. Rep.* **8**, 7452 (2018).
51. Mehta, M., Singh, R., Singh, A. & Singh, N. Recent global aerosol optical depth variations and trends—A comparative study using MODIS and MISR level 3 datasets. *Remote Sens. Environ.* **181**, 137–150 (2016).
52. Jain, S. K., Kumar, V. & Saharia, M. Analysis of rainfall and temperature trends in northeast India. *Int. J. Climatol.* **33**, 968–978 (2013).
53. Machiwal, D., Gupta, A., Jha, M. K. & Kamble, T. Analysis of trend in temperature and rainfall time series of an Indian arid region: comparative evaluation of salient techniques. *Theor. Appl. Climatol.* **136**, 301–320 (2019).
54. Pingale, S. M., Khare, D., Jat, M. K. & Adamowski, J. Spatial and temporal trends of mean and extreme rainfall and temperature for the 33 urban centers of the arid and semi-arid state of Rajasthan, India. *Atmos. Res.* **138**, 73–90 (2014).
55. Radhakrishnan, K., Sivaraman, I., Jena, S. K., Sarkar, S. & Adhikari, S. A climate trend analysis of temperature and rainfall in India. *Clim. Chang. Environ. Sustain.* **5**, 146 (2017).
56. Meshram, S. G. et al. Long-term temperature trend analysis associated with agriculture crops. *Theor. Appl. Climatol.* **140**, 1139–1159 (2020).
57. Jhajharia, D., Dinpashoh, Y., Kahya, E., Choudhary, R. R. & Singh, V. P. Trends in temperature over Godavari River basin in Southern Peninsular India. *Int. J. Climatol.* **34**, 1369–1384 (2014).
58. Khan, M. H. R. et al. Detection of changes and trends in climatic variables in Bangladesh during 1988–2017. *Heliyon.* **5**, e01268–e01268 (2019).
59. Hussain, A. et al. Spatiotemporal temperature trends over homogenous climatic regions of Pakistan during 1961–2017. *Theor. Appl. Climatol.* **153**, 397–415 (2023).
60. Rao, B. B., Chowdary, P. S., Sandeep, V. M., Pramod, V. P. & Rao, V. U. M. Spatial analysis of the sensitivity of wheat yields to temperature in India. *Agric. Meteorol.* **200**, 192–202 (2015).
61. Coast, O., Šebela, D., Quiñones, C. & Jagadish, S. V. K. Systematic determination of the reproductive growth stage most sensitive to high night temperature stress in rice (*Oryza sativa*). *Crop Sci.* **60**, 391–403 (2020).
62. Wang, Y. et al. Flowering dynamics, pollen, and pistil contribution to grain yield in response to high temperature during maize flowering. *Environ. Exp. Bot.* **158**, 80–88 (2019).
63. Zhao, C. et al. Temperature increase reduces global yields of major crops in four independent estimates. *Proc. Natl. Acad. Sci.* **114**, 9326–9331 (2017).
64. Gourdji, S. M., Sibley, A. M. & Lobell, D. B. Global crop exposure to critical high temperatures in the reproductive period: historical trends and future projections. *Environ. Res. Lett.* **8**, 24041 (2013).
65. Bhati, A., Kumari, S. & Kumar, R. Effect of climate changing on horticultural crops in India—a review. *Trends Biosci.* **11**, 1–5 (2018).
66. Jagadish, S. V. K., Murty, M. V. R. & Quick, W. P. Rice responses to rising temperatures–challenges, perspectives and future directions. *Plant. Cell. Environ.* **38**, 1686–1698 (2015).
67. Gupta, A. & Pathak, H. *Climate Change and Agriculture in India*. New. Delhi (2016).
68. Pathak, H. Impact, adaptation, and mitigation of climate change in Indian agriculture. *Environ. Monit. Assess.* **195**, 52 (2023).
69. Dinpashoh, Y., Mirabbasi, R., Jhajharia, D., Abianeh, H. Z. & Mostafaeipour, A. Effect of short-term and long-term persistence on identification of temporal trends. *J. Hydrol. Eng.* **19**, 617–625 (2014).

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Conceptualization: R.N.S. and S.S.; Methodology: R.N.S., S.S., and B.D.; Formal analysis: R.N.S., S.S., and B.D.; Writing—original draft: R.N.S., R.J. and S.S.; Writing—review and editing: R.N.S., A.K.S., K.S.R. and H.P.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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