



Dissecting regional changes in climate variables for crop management studies using probabilistic convolution neighbourhood technique over Kerala

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Abstract

In light of the rapidly growing agricultural sector, spotting signs of climate change is crucial. Even a slight change in climate behaviour can hinder crop development. As a result, it is necessary to investigate these climatic signals at a localised regional scale. The current methods mainly emphasise on outliers when identifying abnormalities in geographical and temporal data. This disregards the possibility of negative impacts brought on by climatic changes at each location. This paper introduces a novel mathematical approach, named the probabilistic convolution neighborhood technique (PCNT), that finds the temporal and spatial coherence at each point. Its ability to examine distribution at all grid points makes it easy to identify even a slight change in climatic variables. This new approach has been applied to study the variations in parameters, namely humidity, precipitation, mean, and maximum temperatures, that are collected from the Indian Monsoon Data Assimilation and Analysis (IMDAA) for the time period 1980 to 2020. The datasets are daily single-level datasets from which annual and seasonal (Kharif, Rabi, and Zaid) data are obtained. Spatio-temporal properties, along with inter-vicennial and inter-decadal variations of climatic variables with regions having low, high, and normal probability distributions, are studied. The findings showed a pattern in the temporal features between Kharif and Rabi. The mean temperature for the annual and seasonal data showed decreasing trends for tail diagnostics. The study brings out an understanding in the probable change in various metrics, which are crucial in the context of crop growth and agricultural practice.

1 Introduction

In India, agriculture has been a part of human civilization for centuries, moulding it into the most prominent sector. The direct contribution of this sector may seem to be minimal; however, it accounts for about 17 to 18% of the country's GDP (Gross Domestic Product) and provides employment for a larger population (Nath et al. (2020)). Over 43% of the nation's geographical area is used for farming, making India the second-largest producer of agricultural products (Pant et al. (2010)).

Food demand has surged due to the drastic population growth. To satisfy the need for food, there is always a need to enhance food production (Saranya and Amudha (2016)). Agriculture is impacted by several elements, none of which are interrelated. Many factors, including climate, terrain, history, geography, biology, politics, institutions, and socioeconomic issues, have an impact on Indian agriculture. Therefore, this potential risk affects the ongoing production of food as well (Mishra et al. (2016)).

Global warming and other climatic changes are mostly due to man-made greenhouse gas emissions, which are caused by industrialisation and urbanisation (Raj and Singh (2012)). The sector most vulnerable to climate change is agriculture (Motha and Baier (2005)). The estimate put forward by FAO (Food and Agriculture Organization) points out that by 2100, climate change-related agricultural losses in Nigeria and other West African nations might reach 4% (Food and Agricultural Organisation, Annual Statistical Report (2005)). Many of the issues confronting agricultural products are climate-related, according to Ayoade (Ayoade (2002)). Based on the findings, by the year 2050, the production of corn

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would fall by 20–40% as a result of climatic changes (Leng and Huang (2017)) in Contiguous United States. In a research conducted in northeast China, relationship between spring maize yield and other climate factors were found. The main climatic parameters limiting the yield of spring maize were then determined (Zhao et al. (2015)). Another study conducted in 2015 (Ray et al. (2015)) indicates that climate fluctuation has a significant impact on crop yield. Crop yields have already declined due to climate change in a number of areas; for instance, it has been reported that between 1981 and 2002, the worldwide production of maize fell by 12 Mt a year (Lobell and Field (2007)). Furthermore, the effects of climate change on agriculture using crop yield simulation models such as CORAC (Mozny et al. (2009)) or statistical models, (Roudier et al. (2011)) suggest that climate change may limit crop production. The first stage in assessing the impact of climate change on crops is quantifying changes in climate variables such as temperature and precipitation (IPCC-TGICA (2007)).

According to the report of IPCC 2007, a rise in global temperature of about 0.74°C from 1906 to 2005 is recorded (Gohari et al. (2013)). Temperature increase, has an impact on most crops, resulting in decreased crop yields and complex growth responses. As per a study, an increase in the temperature by 1°C may lower wheat productivity by 3–10% (You et al. (2009)); and under future warmer and drier conditions, winter wheat production would be lowered by 5–35% (Özdoğan (2011)). The pace of physiochemical reactions and the rate at which water evaporates from crops and soil surfaces are both influenced by temperature, which also has an impact on grain production (Ismaila et al. (2010)). Changes in precipitation levels and patterns are also caused by global warming due to increased evapotranspiration and water vapour levels in the atmosphere (Zhang et al. (2008)). This shift generates extreme events such as drought and flooding, which may have an impact on agriculture (Coscarelli and Caloiero (2012))(Caloiero (2014)). One such example is the winter drought of 2008/2009 which, caused a considerable loss in crop productivity in Nepal (Mishra and Tripathi (2010)).

India is also regarded as one of the most sensitive countries to climate change (INCCA (Indian Network for Climate Change Assessment) (2010)), which adds a new dimension to the current challenges by posing a substantial threat to Indian agriculture (Rao et al. (2016)). Farming activities in India are carried out by selecting crops that are specific to the climate, soil characteristics, resource availability, and so on. As a result, agricultural production and productivity are entirely dependent on climatic conditions (Rao et al. (2016)). According to researchers, the periodic droughts that began in 1966 resulted in significant crop loss in India, and if warmer nights and less rainfall had not occurred, rice yield would have increased by about 4% (Auffhammer et al. (2012)).

Another recent study conducted at the Indian Agricultural Research Institute (IARI) indicates that every 1°C increase in temperature during the growing season of wheat may result in a loss of 4–5 million tonnes of wheat production in the future (Mahato (2014)). All of these studies illustrate the impact of climate change on Indian crops. At the moment, annual average agricultural losses due to extreme weather events result in losses estimated to be roughly 0.25 percent of India's GDP (Datta et al. (2022)).

This research focuses on Kerala, one of the smallest states in India, with a high population density (Nithya (2013)). Kerala's agriculture sector employs around 17.15% of the population and contributes approximately 11.6% of the state's GDP (Mathew et al. (2021)). Thus, it is an extremely significant region of India. In a study from 1956 to 2004, the maximum temperature in Kerala increased by 0.64°C , while the minimum temperature increased by 0.23°C (Rao et al. (2009)). Furthermore, studies have been done which show the adverse effects of climate change in Kerala. Crops are also greatly affected by these climatic changes. One such example is the crops grown in Kuttanad, the rice bowl of India. According to initial estimates, farmers in Kuttanad have lost Rs 9608 crore in crops spread across 6582 ha (Varughese (2022)) and the irregular rainfall pattern has caused constant flooding, affecting the crop quality.

Hence, there is an urgent need to study the characteristics of various parameters affecting crops over Kerala. There are various approaches that can be deployed to evaluate and analyse the effect of climate change on agricultural productivity. The three primary types of statistical approaches are the time series method, panel method, and cross-section method. Despite the fact that they have no significant flaws, they are vulnerable to issues with co-linearity between predictor variables such as temperature and precipitation (Lobell and Burke (2010)). Ecophysiological models (White et al. (2011)) and crop simulation models, such as the decision support system for agrotechnology transfer (DSSAT) (Dias et al. (2016)), are often used to examine the impact of climatic factors on crop growth. Some of the techniques used in machine learning include artificial neural networks (ANN), information fuzzy networks, and decision trees (Mishra et al. (2016)).

In each of the aforementioned situations, it is crucial to first look at the variations in climate factors throughout a certain time period in a region. In order to study the variations in climatic variables affecting crop yield, both the spatial and temporal variations must be analysed. Many of the studies like (Zhao et al. (2018)), (Prävälíe et al. (2019)), (Huang et al. (2016)), (Gocic and Trajkovic (2014)), (Song et al. (2019)), and (Toros (2012)) focus on either temporal or spatial differences. Location-wise analysis (LWA) is a standard methodology that is used to find anomalies in spatial and temporal data separately. But the major drawback

faced by this technique is that it neglects temporal and spatial coherence (Mitra and Seshadri (2019)) single time. To rectify this drawback, in 2019 researchers developed a new method called Markov random fields (MRFs) that considers both the coherences (Mitra and Seshadri (2019)). Studies (Nanzad et al. (2019)), (Mukherjee et al. (2023)), and (Wu et al. (2008)) are a few examples of other research works that have been established to find anomalies. Each of these methods, however, simply considers the variations in the outliers, ignoring the potential impact that even a slight modification at any time could have profound effects. Therefore, climatic variations at points must be examined, including outliers.

In this study, the objective is to develop a method that analyse variations in every single grid point taking into account the spatio-temporal coherence. One such novel approach developed in this study is the probabilistic convolution neighbourhood technique (PCNT). The benefits of PCNT include the ability to observe distributional changes at all grid points and the fact that every point is affected by neighbouring points, which aids in the analysis of regional variations in meteorological data useful for identifying changes in crops. Climatic variables like relative humidity, maximum temperature, mean temperature, and precipitation are considered. These changes are analysed annually as well as in the three crop seasons of Kerala: Kharif (June to September), Rabi (October to March), and Zaid (between March and June) (PscAriVukal (2020)).

The entire manuscript is arranged in the following way: the data acquired and the methodology used are discussed in Section 2, in Section 3, the results and findings are explained, and the results are discussed in Section 4. The study is finally concluded in Section 5.

2 Materials and methods

2.1 Study area

Kerala is a state on the Malabar Coast of India, located between $8.15^{\circ}N$ and $12.50^{\circ}N$ and latitudes and between $74.50^{\circ}E$ and $77.30^{\circ}E$ longitudes. The state is approximately 570kms long and 120kms wide at its widest point, spanning an area of around 3.8 million hectares (Mathew et al. (2021)). Kerala has a wet and maritime tropical climate affected by the southwest summer monsoon and the northeast winter monsoon. Approximately 65% of the rainfall is received between June and August ($2250\text{--}2500\text{ kg/m}^2$), corresponding to the southwest monsoon, and the remainder falls between September and December ($450\text{--}500\text{ kg/m}^2$), relating to the northeast monsoon (Planning Commission, India (2007)). The average daily temperature ranges from 292.95 to 309.85 Kelvin (Sudha (2011)). Mean yearly temperatures in the coastal lowlands range from 298.15–300.65

to 293.15–295.65 K in the eastern highlands (Brenkert and Malone (2003)).

2.2 Data

IMDAA daily single-level dataset for the parameter's relative humidity, maximum temperature, mean temperature, and precipitation is taken from the National Centre for Medium-Range Weather Forecasting (NCMRWF) website (Rani et al. (2021)). It offers 12 km/h high-resolution data. The available data had values for the whole of India, from which the values of Kerala (Fig. 1) were acquired. Mean and maximum temperature data were given in Kelvin, precipitation in kg/m^2 , and relative humidity in percent. All the grid points located within Kerala, which are 234 in number, are found, and their latitude and longitude are determined. The data values at these points for the climatic variables under study are extracted.

The seasonal data of paddy crops were taken from the website of the Department of Economics and Statistics, for the state of Kerala (1980–1981 to 2019–2020), and its districts (2004–2005 to 2019–2020).

As the current study's objective is to look into the changes in climatic variables caused by the varying climatic conditions, data from 41 years (1980–2020) is considered.

The aforementioned climatic variables were also used to create a dataset for the seasons of Kharif (June to September), Rabi (October to March), and Zaid (between March and June).

2.3 Methodology

In this section, detailed information will be given about the proposed methodology. To derive the method, firstly different components namely convolution and fitting of Gamma distribution are described. Following that, a thorough explanation of the PCNT approach is provided.

2.3.1 Convolution

Convolution can be conceptualised as a function that measures the degree of overlap as one function is shifted over another and is the integral or sum of two component functions (Kim and Casper (2013)). Mathematically, if f is an integrable function defined on R^n and g is a bounded, locally integrable function then the convolution product of f and g is the function R^n defined by the integral

$$f^*g(x) = \int_{\mathbb{R}^n} f(x-y)g(y)dy \quad (1)$$

In other words, Eq. 1, describes how much a function, g , overlaps with another function f when they are shifted over

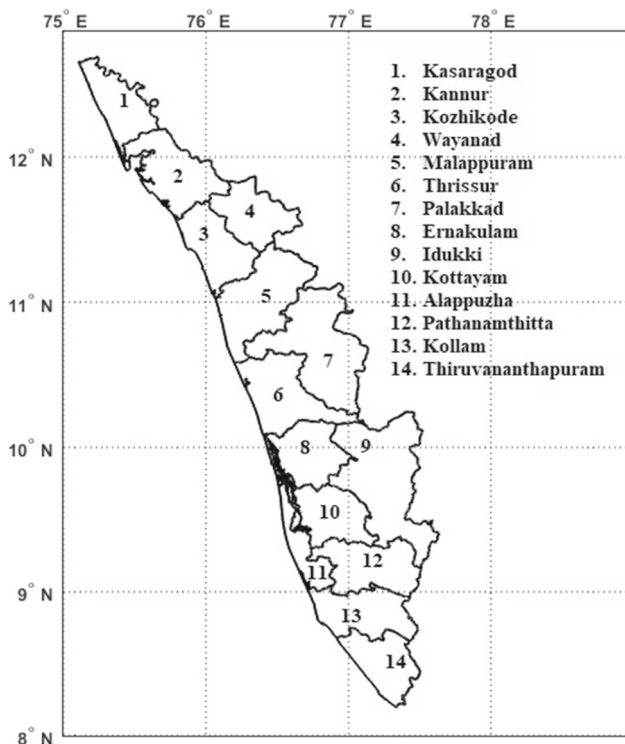


Fig. 1 The study area - Kerala

one another (Daners (2019)). When the same idea is applied to images, it results in convolution in 2D (Sameer (2021)). In the concept of convolution 2D, a mathematical operation and a matrix are applied to an image, producing a filter effect on the images. It operates by combining the values of the core pixels, which are calculated using the weighted average of all of their neighbouring values (Ludwig (2007)). The mathematical formulation of 2-D convolution is given by

$$y[i, j] = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} h[m, n] \cdot x[i - m, j - n] \quad (2)$$

where in Eq. 2, the kernel matrix h and the input image matrix x are convoluted to create the new matrix y , which represents the output image. Here, the indices i and j deal with the image matrices, while m and n deal with the kernel matrices (Sneha (2018)).

2.3.2 Gamma distribution

For values of $x > 0$, the Gamma function is defined using an integral formula as in Eq. 3.

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt \quad (3)$$

The Gamma distribution's probability density function is represented by the following formula as in 4,

$$P(x) = \frac{x^{\alpha-1} e^{-\frac{x}{\beta}}}{\beta^{\alpha} \Gamma(\alpha)} \quad (4)$$

The mean of the Gamma distribution is $\alpha\beta$ and the variance is $\alpha\beta^2$ (Hosch (2022)).

Due to its statistical properties, including skewness with few locations showing high frequencies when taking only the positive values into consideration, the Gamma distribution is judged to be the best fit for describing the rainfall data (Sivajothi and Karthikeyan (2016), Papalexioiu and Koutsoyiannis (2012), Koutsoyiannis and Onof (2001)). Similar to rainfall, all parameters considered in the study depict the same property; hence in all other cases Gamma distribution is employed.

2.3.3 Probabilistic convolution neighbourhood technique

Every grid point within the domain under consideration has been subjected to the PCNT method. To evaluate the spatio-temporal coherence all at once, the basic idea is to convolute around the fixed points with a specified radius and fit a Gamma distribution. The steps of the process are listed below:

1. A gridpoint from the domain is selected;
2. In each of the points in step 1, the theory of convolution is applied. Here, in Eq. 2, the input x is taken as the image of Kerala and h , a circle with a fixed radius as shown in Eq. 5;

$$h(x) = \sqrt{(x - x_0)^2 + (y - y_0)^2} \leq 0.5 \quad (5)$$

3. All the data points inside and on the circle from step 2 are extracted;
4. The points obtained in step 3 are then fitted with the Gamma distribution;
5. The process is repeated for each gridpoint until all the points are convoluted.

2.3.4 Selection of quartiles

To evaluate the changes in the parameters, the quartile differences are found based on the probabilities of Gamma distribution. The lower quartile is considered for the probability less than 0.30 while the upper quartile is considered for ≥ 0.95 probabilities. The normal is considered between ≥ 0.30 and < 0.95 (Dash et al. (2011)).

All results were performed using Matlab software.

3 Results

Even under normal conditions, a small change in the weather can have a direct and indirect impact on crop growth. This may have a detrimental effect on people's quality of life. For instance, as the population increases, so does the need for food. Variations in the weather, such as rising carbon dioxide levels and shifts in temperature, radiation, and rainfall, have an impact on crop growth and output, leading to a food crisis that has an influence on people's livelihoods (Rial-Lovera et al. (2017))(Daloz et al. (2021))(Lal et al. (2020)). Examining these significant changes in parameters and taking the appropriate measure, to some extent can help in enhancing crop growth.

Due to the limited usage of the IMDAA dataset in research studies, it is vital to examine the temporal and spatial properties of each of the climatic variables; relative humidity, precipitation, and maximum and mean temperature on an annual and seasonal timescale.

3.1 Temporal changes on the annual and seasonal timescale

3.1.1 Climatological average change

To comprehend the data more clearly, properties namely, maximum and minimum values, mean, median, skewness, kurtosis, standard deviation, and coefficient of variation, for temporal data are found. Table 1 shows the values obtained for annual and seasonal temporal data.

The annual relative humidity ranges from 78.42 to 82.69%. The dataset for humidity has a maximum standard deviation of 1%, which indicates that it is widely dispersed when compared to other variables. The maximum and minimum values obtained by mean temperature are 299.56 K and 298.63 K, respectively, whereas the maximum temperature fluctuates between 303.62 and 302.19 K. Both these temperature variables have negative skewness, stipulating that more of the data values are clustered around the right tail. The annual precipitation is positively skewed with a high coefficient of variation and ranges from 5.71 kg/m² to a maximum of 9.82 kg/m².

The characteristics of the temporal data for the three seasons of Kharif, Rabi, and Zaid are shown in Table 1. Comparing the three seasons, Kharif showed maximum relative humidity (90.59%), while Rabi showed the minimum (72.60%). The highest maximum temperature was obtained for the season Zaid (306.70 K), whereas Kharif (299.73 K) recorded the lowest. Compared to the other two seasons, the standard deviation of the maximum temperature was lower in Kharif season, thus showing less dispersion of data from the mean. Kharif has the highest recorded precipitation (18.79 kg/m²) and Rabi has the lowest (2.10 kg/m²) values.

The seasons with the highest and lowest mean temperatures are Zaid (302.13 K) and Kharif (297.42 K), respectively. The skewness of the relative humidity is positive during the Rabi season (0.62%) and negative during Kharif (−0.47%) and Zaid (−0.04%). This shows that the relative humidity data values for Rabi are concentrated around the left tail, and for both Kharif and Zaid, they are concentrated on the right tail. The standard deviation of precipitation has the lowest value in the Rabi (0.71 kg/m²) season. Skewness for maximum temperature is negative in both Rabi (−0.53 K) and Zaid (−0.51 K) whereas it is positive for Kharif (0.13 K). The kurtosis for the three seasons is platykurtic for relative humidity, leptokurtic for maximum temperature in Kharif and Zaid, and platykurtic for Rabi. The same is true for the mean temperature. In the event of precipitation, Rabi and Zaid are leptokurtic, while Kharif is platykurtic. The coefficient of variation of precipitation is the highest during Zaid.

It is seen from the above analysis that the lowest relative humidity reading is depicted by Rabi, which contributes to the region's low precipitation levels. Kharif, on the other hand, had the highest relative humidity and the most

precipitation. A similar observation was made by Goparaju and Ahmad (2019). Kharif experiences a drop in temperature because of the high rate of precipitation. The kurtosis of all the climatic variables indicates that the data values on an annual and seasonal period congregated in the distribution's tails.

This observation suggests that the state's distribution of various climatic parameters varies from season to season—for instance, precipitation (Jagannathan and Bhalme (1973)).

3.1.2 Year to year temporal variability

The available daily single-level data sets are used to obtain year-to-year data in order to observe the temporal variations from 1 year to the other. The temporal changes in the variables (relative humidity, precipitation, mean, and maximum temperatures) over Kerala are normalised and depicted in Fig. 2.

In order to illustrate temporal changes, the variables under consideration—relative humidity, precipitation, mean, and maximum temperatures—are normalised and plotted. The annual humidity reached its highest value in 2010 and its lowest in 1987, as shown in Fig. 2. The observed mean, and maximum temperatures were at their lowest in 1984 and highest in 2019 and 2003, respectively. The maximum and minimum annual precipitation were recorded in 2019 and 1999, respectively.

Comparing the seasonal plots, Zaid recorded the highest humidity in 2004, whereas Rabi observed the lowest. The highest and lowest humidity readings for Kharif were in 2010 and 1987, respectively. For both the Kharif and Rabi seasons, the mean temperature peaked in 2015. Mean temperatures for

Table 1 Temporal properties for climatic variables on annual and seasonal timescale

Annual	Relative humidity(%)	Maximum temperature(<i>K</i>)	Mean temperature(<i>K</i>)	Precipitation(<i>kg/m</i> ²)
Maximum value	82.68918	303.6181	299.563	9.8177
Minimum value	78.4182	302.1915	298.6337	5.7128
Mean	80.35916	302.9546	299.1013	7.326595
Median	80.14182	303.0283	299.0838	7.237265
Skewness	0.248821	-0.29662	-0.04585	0.288205
Kurtosis	2.45015	2.337537	2.01247	2.321048
Standard deviation	1.036643	0.34078	0.267849	0.975244
Coefficient of variation	1.290013	0.112485	0.089551	13.31102
Kharif				
Maximum value	90.59497	301.5735	298.8964	18.78918
Minimum value	86.25334	299.73	297.417	8.951166
Mean	88.89232	300.6064	298.2169	13.59201
Median	89.07091	300.634	298.247	13.32211
Skewness	-0.47075	0.132581	-0.18384	0.133029
Kurtosis	2.322869	3.493598	3.323055	2.237273
Standard deviation	1.155065	0.385307	0.298371	2.51256
Coefficient of Variation	1.299398	0.128177	0.100052	18.48556
Rabi				
Maximum value	80.54224	304.6651	299.77	5.266026
Minimum value	72.59506	302.4382	298.4234	2.099926
Mean	75.45559	303.7081	299.0298	3.418271
Median	75.38669	303.7887	299.0255	3.29191
Skewness	0.617689	-0.52645	0.248828	0.698424
Kurtosis	2.981556	2.376937	2.203905	3.09025
Standard deviation	1.820957	0.537413	0.36808	0.71335
Coefficient of variation	2.413282	0.17695	0.123091	20.86874
Zaid				
Maximum value	82.8223	306.7011	302.1305	11.31115
Minimum value	72.79187	303.4416	299.7923	3.861242
Mean	77.94497	305.384	301.0822	6.511308
Median	77.91984	305.4394	301.0667	6.32471
Skewness	-0.03677	-0.51327	-0.28041	0.82102
Kurtosis	2.80758	3.019079	3.242417	3.639778
Standard deviation	2.21406	0.770207	0.477029	1.591809
Coefficient of variation	2.840543	0.252209	0.158438	24.44684

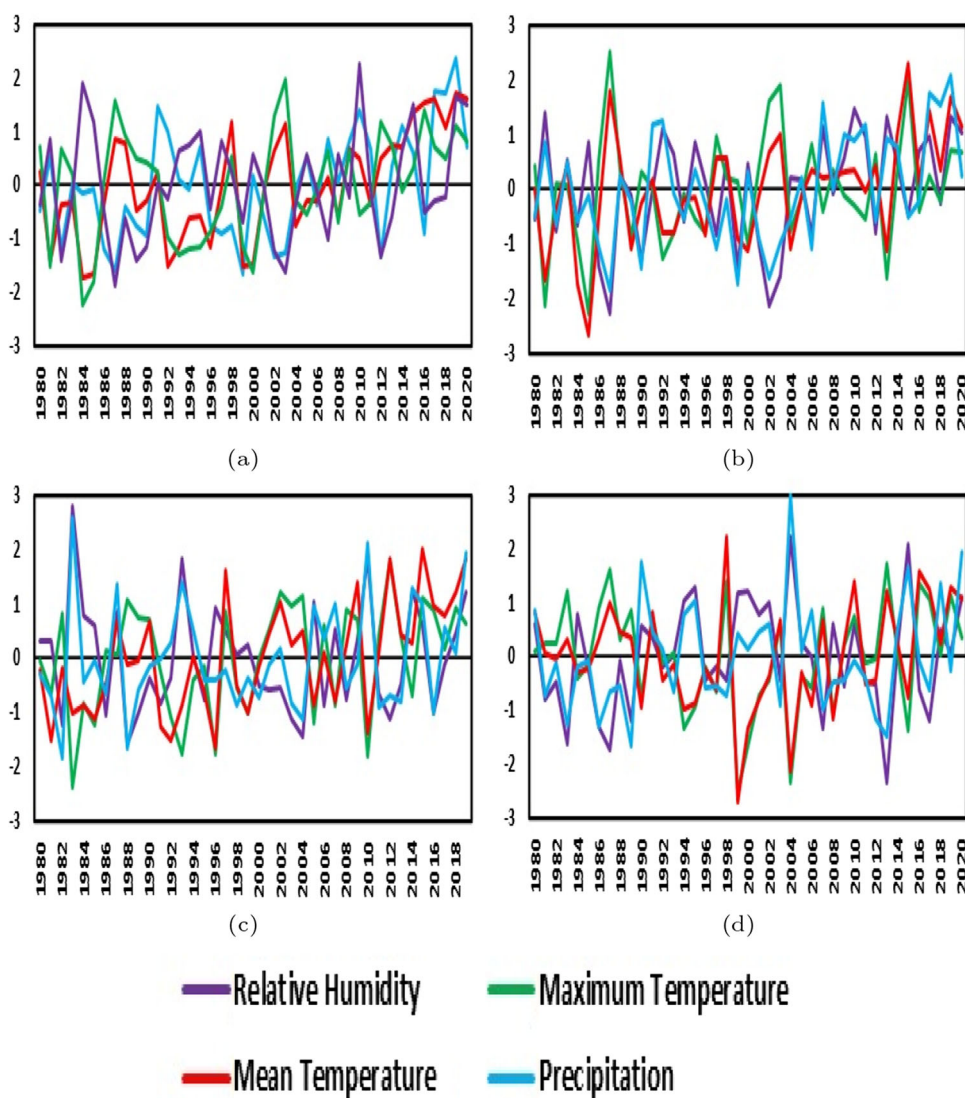
the years 1998 and 1999 were found to be highest and lowest during Zaid, respectively. Maximum rainfall was observed in 2019 for Kharif, 1983 for Rabi, and 2004 for Zaid.

Analysing the Kharif season, it is observed that in 1987, humidity and precipitation were the lowest and maximum temperature the highest. India experienced a similar phenomenon (Krishna Kumar et al. (2004)). A trend contrary to Kharif was seen in 1983 by Rabi. That is low maximum temperature and high humidity and precipitation. During Zaid, this same pattern was repeated in 2004.

To assess the trend of the temporal data, the Mann Kendall (MK) test was applied to the annual and seasonal variables (Güçlü (2020)). The findings revealed an increasing trend in the annual and seasonal timescales for relative humidity, precipitation, maximum, and mean temperatures.

Humidity, maximum, and mean temperatures for the annual data were all statistically significant at levels more than 90%. The observed significance for humidity, mean temperature, precipitation, and maximum and mean temperatures during Kharif and Rabi, respectively, were greater than

Fig. 2 Temporal changes for the variables (a) Annual, (b) Kharif, (c) Rabi, and (d) Zaid



90%. The relative humidity for Rabi and maximum temperature for Zaid were also found to be insignificant as reported by a similar study (Roy (2015)).

3.2 Spatial properties on the annual and seasonal timescale

Since the temporal characteristics depict only the overall average characteristic of Kerala, it is necessary to evaluate the characteristics on a regional spatial scale. The mean and standard deviation for 234 grid points in Kerala have been computed on an annual and seasonal scale.

Figure 3, depicts the mean and standard deviation of the spatial data for the season as a whole. Idukki, Ernakulam, Kottayam, Pathanamthitta, and areas of Wayanad and Kozhikode are found to have relative humidity levels of around 85%, whereas Kasaragod, Palakkad, Thrissur, Kannur, and some parts of Thiruvananthapuram, and Kollam,

have relative humidity levels lying in the range of 70 to 80%. The average maximum temperature for 41 years in Kerala showed high values in regions of Kasaragod, Kannur, Malappuram, Kozhikode, Thrissur, Palakkad, Ernakulam, Kottayam, Pathanamthitta, Kollam, and Thiruvananthapuram. The average temperature was higher in coastal regions. Except for some regions of Kannur, Kozhikode, Wayanad, Idukki, Pathanamthitta, and Kollam, Kerala observed precipitation of about $10kg/m^2$. However, the regions of Thiruvananthapuram, Kollam, and Wayanad recorded the lowest precipitation.

Idukki has several areas with high precipitation compared to other regions of the state, which also happens to have the lowest temperature and maximum humidity. Low precipitation is noted in the districts of Malappuram, Thrissur, and Palakkad along with high temperatures and low humidity.

The standard deviation for the climatic variables for 41 years is shown in Fig. 3. The coastal parts of Kerala displayed a low value for relative humidity, even though some

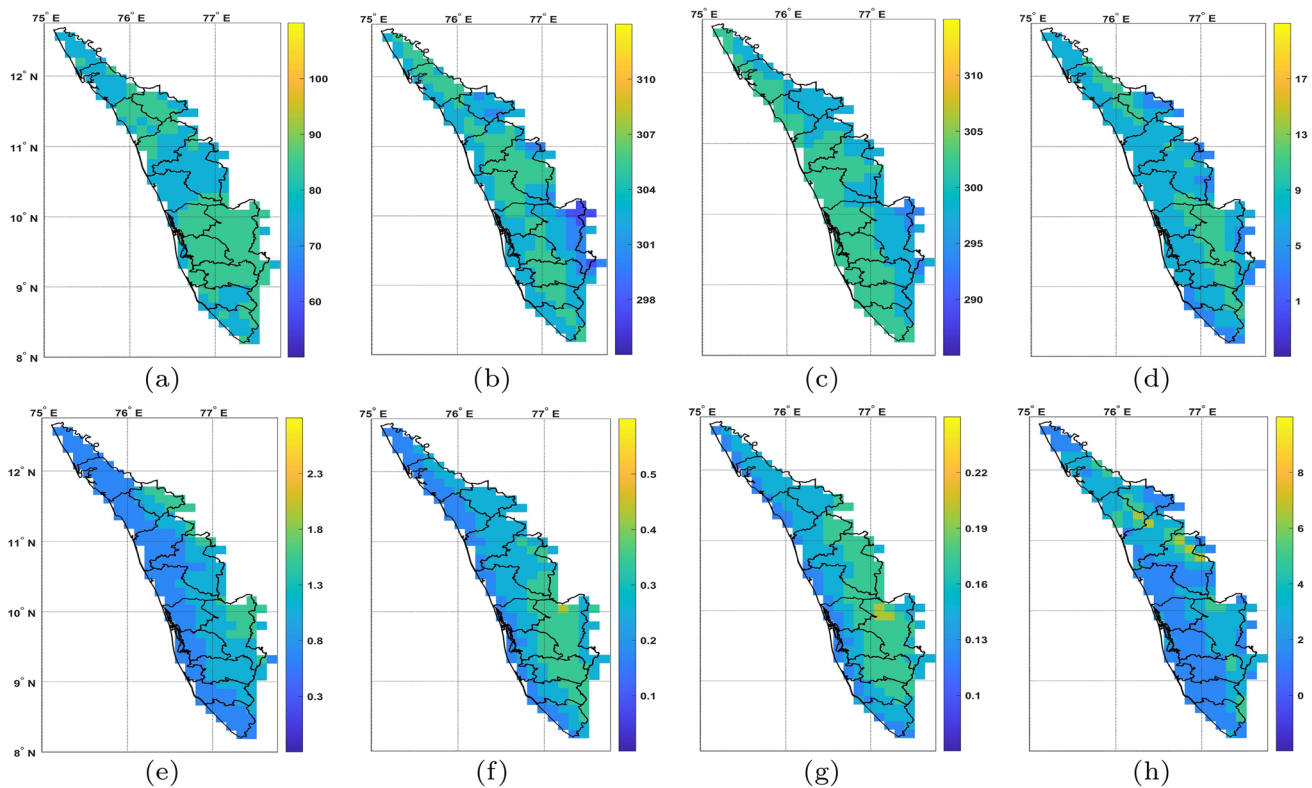


Fig. 3 Annual mean (upper panel) and standard deviation (lower panel) of climatic variables for (a, e) relative humidity, (b, f) maximum temperature, (c, g) mean temperature, and (d, h) precipitation

areas of Wayanad and Idukki displayed a high value (1.8%). Aside from a few places in Palakkad, Idukki, Kottayam, Pathanamthitta, and Kollam, standard deviations for maximum temperatures for all other regions fell between 0.1 and 0.3 K. The maximum and mean temperature values highly deviated from the mean in some areas of Idukki. The regions of Kozhikode, Malappuram, and Palakkad showed high dispersion values for precipitation. A study that was carried out in the districts of Kozhikode and Malappuram lends credence to this fact (Abhinav et al. (2018)).

The mean seasonal spatial images of the climatic parameters are shown in Fig. 4. Various districts, including Idukki, Ernakulam, Kasaragod, Kannur, and Wayanad, get their highest relative humidity readings during Kharif, while the season's maximum temperature is reported to be around 304 K. Kerala experiences roughly the same average temperature throughout the Kharif season. Spatial images captured during the Rabi exhibit that Kerala had practically constant relative humidity. Some areas of Palakkad recorded maximum temperatures of up to 308 K.

The southern regions of Kerala experienced high mean temperature values throughout the Rabi season, apart from Idukki. All districts of Kerala have extremely low levels of precipitation during Rabi except Idukki. During Zaid, relative humidity ranged between 70 and 90% throughout Kerala.

Kerala's northern region displays high maximum temperature readings during this season when compared to the southern region. The mean temperature, however, is almost uniformly distributed. During the season Zaid, Kerala's southern portion experiences comparatively more precipitation than its northern area. As humidity and precipitation rise during the seasons of Rabi and Zaid, temperature drops in the Idukki district. Wayanad and Kannur exhibit the same characteristics during Kharif. As precipitation decreases in Wayanad during Zaid, so do temperatures.

The seasonal standard deviation for each climate variable is shown in Fig. 5. The standard deviation of relative humidity reported levels under 1.3% throughout Kerala during the Kharif season. The districts of Thrissur, Ernakulam, Kottayam, Idukki, Alappuzha, Pathanamthitta, Kollam, and Thiruvananthapuram had finer standard deviation values for the maximum temperature and mean temperature. A few areas in the districts of Kozhikode, Wayanad, Malappuram, Palakkad, Idukki, and Pathanamthitta revealed high values of standard deviation when the spatial image of precipitation was examined. During Rabi, the standard deviation of relative humidity was analysed to be high in some districts, namely, Palakkad and Idukki.

The coastal parts of Kerala reported lower values for the standard deviation of the maximum and mean temperatures.

Fig. 4 Seasonal mean of climatic variables for: Kharif (a) relative humidity, (d) maximum temperature, (g) mean temperature, and (j) precipitation; Rabi (b) relative humidity, (e) maximum temperature, (h) mean temperature, and (k) precipitation; Zaid (c) relative humidity, (f) maximum temperature, (i) mean temperature, and (l) precipitation

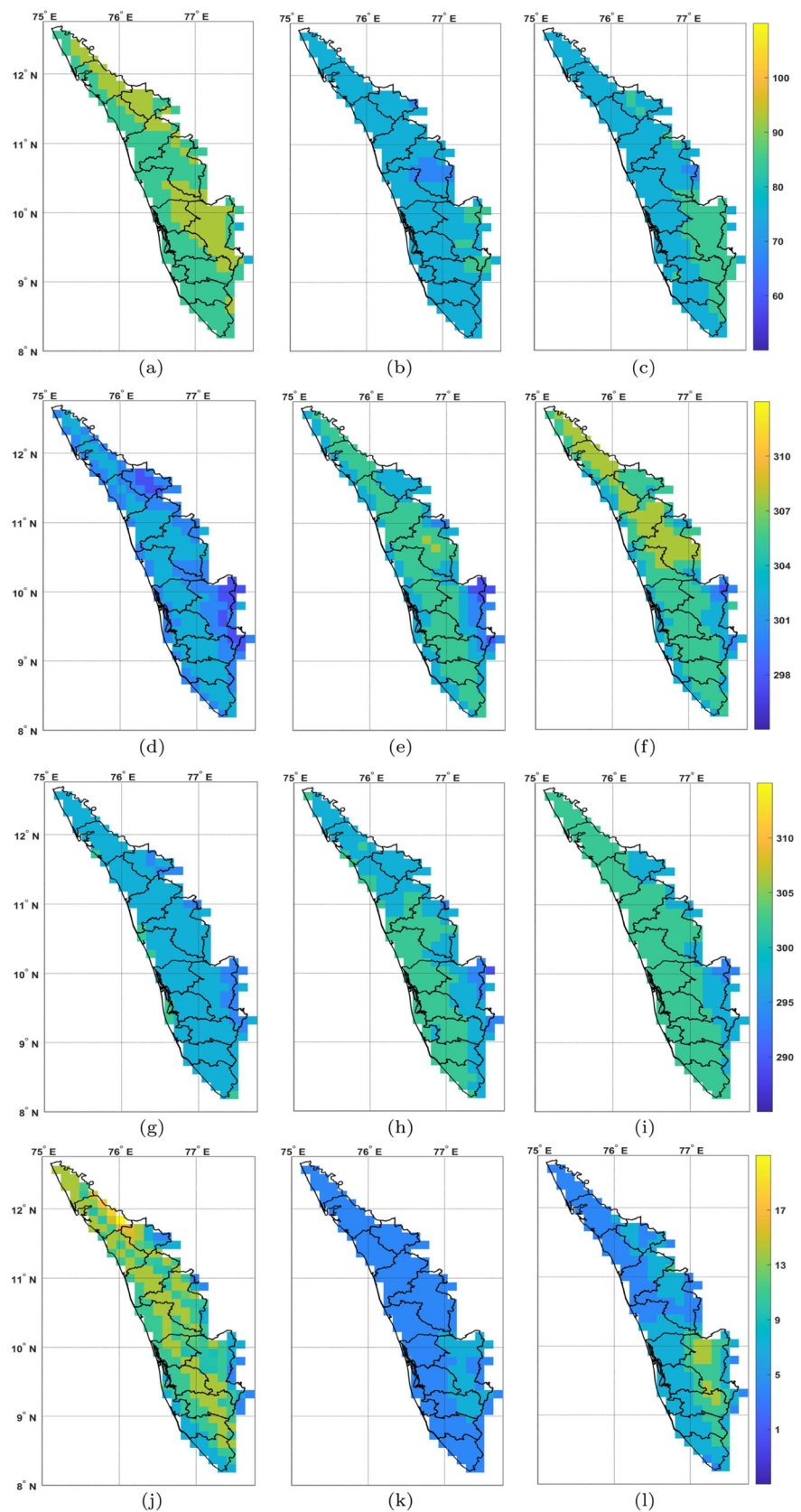
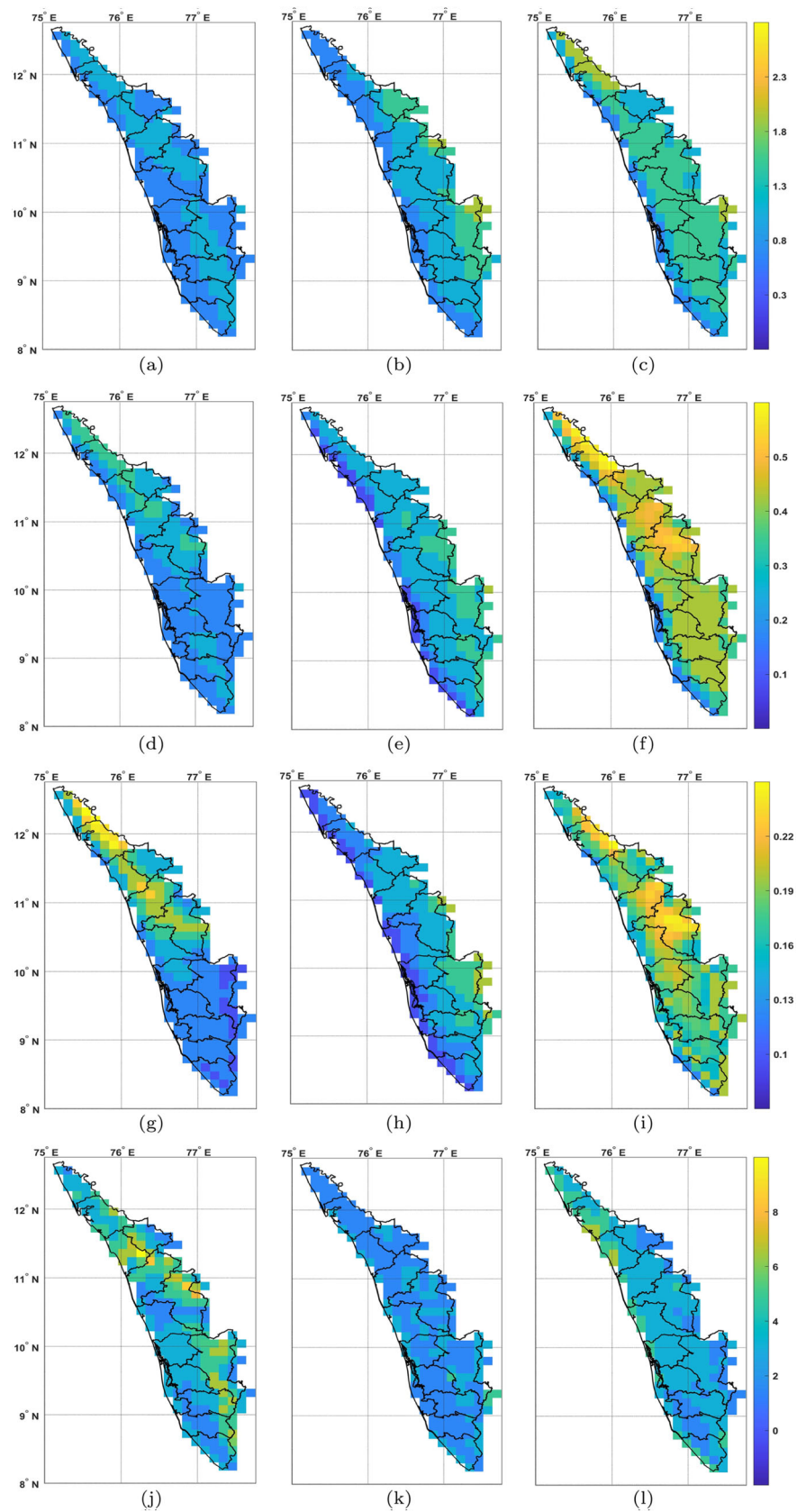


Fig. 5 Seasonal standard deviation of climatic variables for: Kharif (**a**) relative humidity, (**d**) maximum temperature, (**g**) mean temperature, and (**j**) precipitation; Rabi (**b**) relative humidity, (**e**) maximum temperature, (**h**) mean temperature, and (**k**) precipitation; Zaid (**c**) relative humidity, (**f**) maximum temperature, (**i**) mean temperature, and (**l**) precipitation



However, precipitation values remained constant throughout this season. During the month of Zaid, only a few places in Kasaragod and Kannur showed high deviation for relative humidity values, however, other places in Kasaragod, Kannur, Malappuram, and Palakkad showed higher standard deviation for maximum temperature. Significant standard deviations for mean temperature were observed in some areas of Palakkad and Kannur. Other than the districts of Kozhikode, Kannur, and Kasaragod, the standard deviation of precipitation throughout the season is nearly constant.

In comparison to Kharif, Idukki's temperature and relative humidity data are less reliable throughout the seasons of Rabi and Zaid. Rainfall for the same district in comparison to Kharif was less consistent. During the seasons of Kharif and Rabi, Kerala's southern region experienced the least deviation in temperatures.

To evaluate the current changes, the variables are first divided into two periods. The first phase lasted from 1980 to 2000, and the second from 2001 to 2020. The above-proposed technique has two applications. The first strategy, tail diagnostics, finds and compares the differences between the upper quartiles of the two periods and the lower quartiles of the two periods. This assesses the variations in climatic variables over two timelines, highlighting the regions with high and low differences. In the second approach, maximum areal difference, the difference between the upper and lower quartile is found and compared for each time. This provides the disparities between the periods having normal values. The same is done to find the Inter decadal changes, where difference of 10 years are taken. Spatial images of the values thus obtained are plotted for easy understanding and comparison.

3.3 Inter-viceennial changes

To examine the variations in the climatic variables in this section, the differences between the two periods are found by deducting the values of period 1 (1980–2000) from period 2 (2001–2020).

The highest relative humidity values at both times were found in Ernakulam, Idukki, Kottayam, and Pathanamthitta, as seen in Fig. 6. The changes that have occurred across both of these periods are depicted on the difference map. The above-mentioned district's differences in values ranged from 0.3 to -0.3% . Positive changes in specific areas of Kasaragod, Kannur, Kollam, and Thiruvananthapuram indicate that relative humidity levels in these areas during period 2 were higher. Kozhikode, Malappuram, and Ernakulam regions all exhibited a maximum temperature greater than 0.1 K on the difference map. Period 1 had higher maximum temperatures than period 2 in several regions of Wayanad, Idukki, Palakkad, Kottayam, Pathanamthitta, Kollam, and Thiruvananthapuram. A wide range of negative deviations in mean temperature was seen in parts of Kannur, Wayanad,

Kozhikode, Malappuram, Thrissur, Palakkad, and Ernakulam. In certain areas of Kannur, the amount of precipitation that fell over the two time periods was nearly the same.

Thiruvananthapuram observed an increase in the maximum temperature, humidity, and precipitation compared to period 1. For each period, the maximum temperature decreased along with the humidity and precipitation. The pattern that was noticed in the temporal and spatial features is not present here. All district's mean temperature dropped in period 2. In the districts of Malapuram and Kozhikode, relative humidity increased as well as decreased in both periods.

Figure 7 depicts the differences between the two time periods for all climate variables for the three seasons of Kharif, Rabi, and Zaid. The difference between the two periods during Kharif indicates that all districts in period 2 had higher relative humidity than period 1. Kozhikode, Wayanad, Malappuram, Thrissur, and the borders of Palakkad, Ernakulam, Kottayam, Alappuzha, Idukki, and Pathanamthitta all experienced relative humidity differences of roughly 0.3% . In the case of Rabi, indicating that period 1 had the highest value in these areas, a difference of -0.6% was seen in Kozhikode, Wayanad, Malappuram, Thrissur, Palakkad, Ernakulam, Kottayam, and Alappuzha. Only some areas of Idukki experienced negative differences during the Zaid season. Kannur marked positive humidity with a difference greater than 0.9% . During Kharif, a positive difference in maximum temperature was observed in Thrissur, Palakkad, Ernakulam, Idukki, Kottayam, Alappuzha, and Pathanamthitta. Kasaragod experienced a constant maximum temperature in both periods. The maximum temperature varies during the three seasons in both positive and negative directions. The areas of Thiruvananthapuram, Kollam, Pathanamthitta, Idukki, and Palakkad showed the largest negative fluctuations during Rabi. Meanwhile, Wayanad, Malappuram, Thrissur, Palakkad, Ernakulam, Alappuzha, Kottayam, and Idukki all had a mean temperature greater than -0.2 K . During Zaid, variances in maximum temperature readings of roughly -0.2 K were recorded in Kannur, Wayanad, Malappuram, Palakkad, Idukki, Pathanamthitta, and Kollam. The difference in mean temperature for this season is consistently negative, showing that period 1 had higher values than period 2. The differences in precipitation during the Kharif season are all negative, except in some areas of Kannur. While in Rabi, all regions except for a small portion of Idukki displays a negative value. When compared to other areas, Kerala's coastal regions experienced substantial precipitation differences during the Zaid season.

During Kharif and Zaid, an increase in relative humidity and a decrease in mean temperature is observed in Kerala. In Kasaragod, the maximum temperature is steady during the seasons of Kharif and Rabi. On the contrary, fluctuations

Fig. 6 Annual inter vicennial difference: 1–20 years (a) relative humidity, (d) maximum temperature, (g) mean temperature, and (j) precipitation; 21–41 years (b) relative humidity, (e) maximum temperature, (h) mean temperature, and (k) precipitation; difference (c) relative humidity, (f) maximum temperature, (i) mean temperature, and (l) precipitation

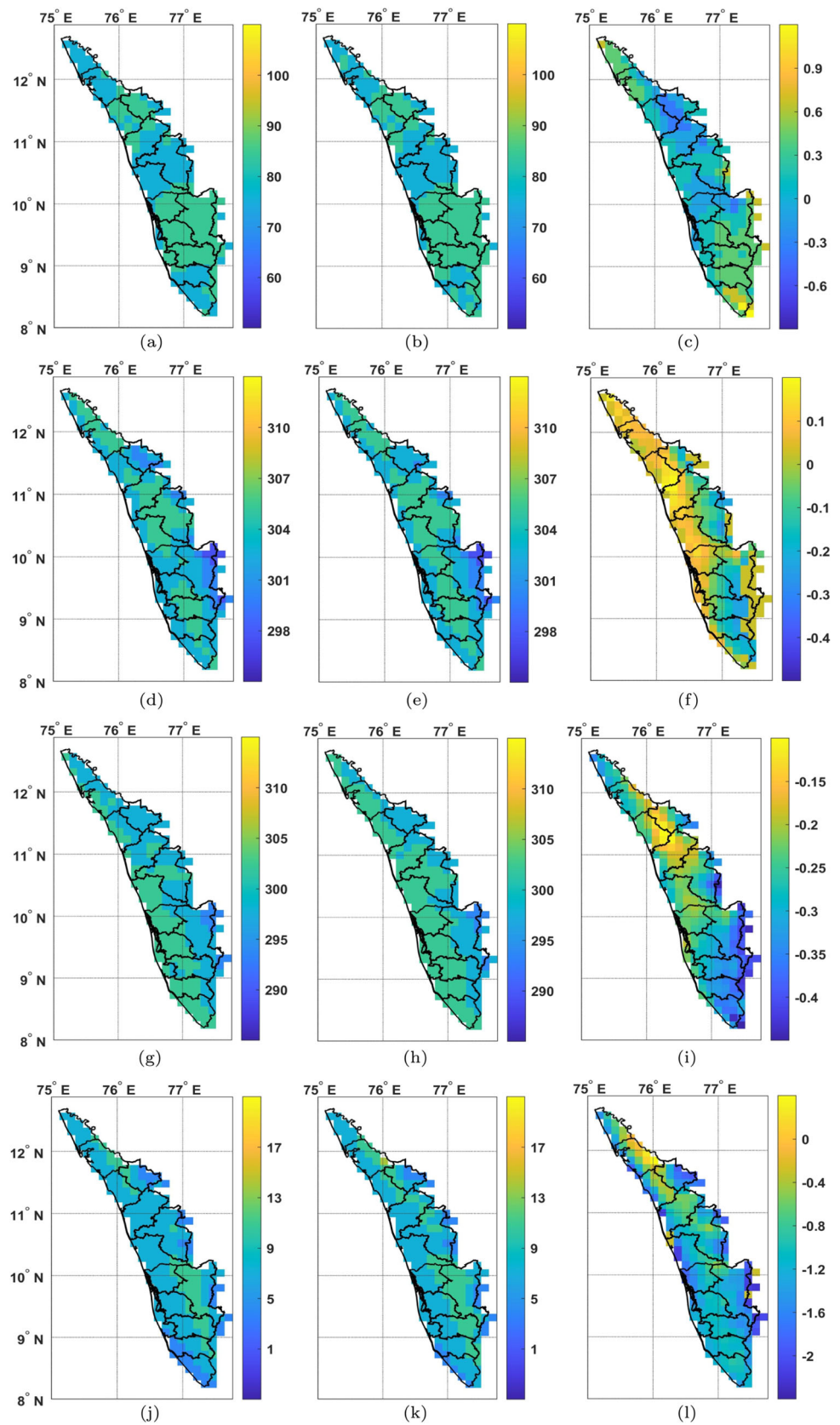
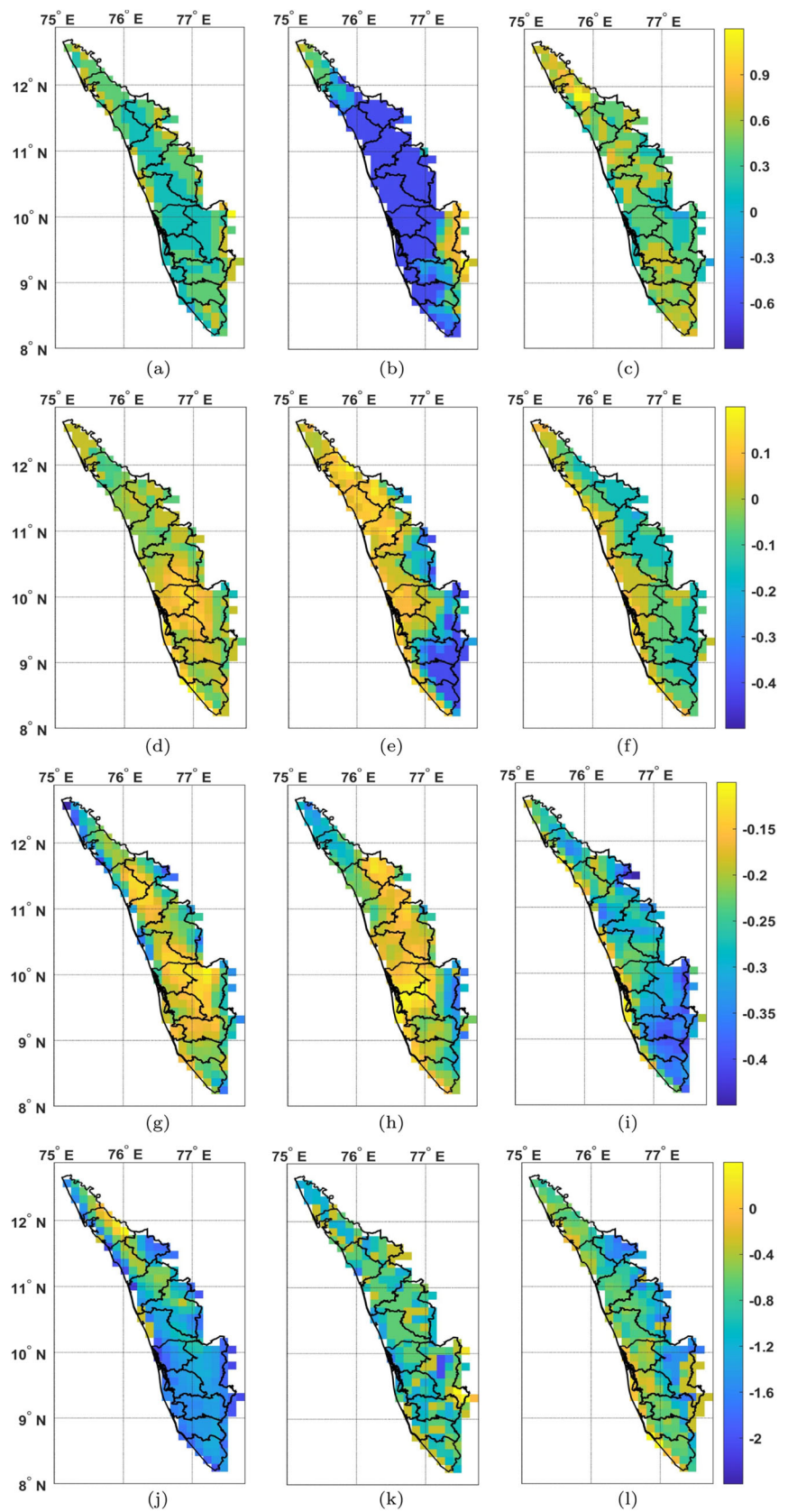


Fig. 7 Seasonal inter vicennial difference: Kharif (**a**) relative humidity, (**d**) maximum temperature, (**g**) mean temperature, and (**j**) precipitation; Rabi (**b**) relative humidity, (**e**) maximum temperature, (**h**) mean temperature, and (**k**) precipitation; Zaid (**c**) relative humidity, (**f**) maximum temperature, (**i**) mean temperature, and (**l**) precipitation



are seen in Zaid. In Kannur, the maximum temperature and precipitation fall off during Zaid and Kharif, but relative humidity increases. Abrupt variations in climatic variables are observed in many parts of Kerala.

3.3.1 The tail diagnostics

The districts Malappuram, Ernakulam and regions of Kannur, Kozhikode, Wayanad, Thrissur, Palakkad, and Idukki all had the same difference in the upper quartiles of the two periods for relative humidity as shown in Fig. 8.

Kasaragod, Thiruvananthapuram, and parts of Kollam and Pathanamthitta districts recorded a difference of 0.5%. Kannur, Thrissur, Palakkad, Ernakulam, Idukki, Kottayam, and Alappuzha are among the regions with values in the lower quartiles, at 0.2%. The northern and southern parts of Kerala have positive relative humidity at both tails. In the upper quartile, Kasaragod, Kannur, Kozhikode, Wayanad, Malappuram, Thiruvananthapuram, and some regions of Kollam recorded positive differences in maximum temperatures. Kasaragod and Kannur exhibited a high positive difference in the lower quartile and negative differences in the lower part of Kerala. When the mean temperatures are examined, a value of about $-0.25K$ is found in several areas of Kannur, Thrissur, Palakkad, Ernakulam, Kottayam, and Idukki, in the upper

quartile, while the same difference is found in Thrissur, Palakkad, Kottayam, Alappuzha, and Ernakulam in the lower quartile.

Parts of Malappuram, and Palakkad in the upper quartile and Kozhikode, Wayanad, Malappuram, Palakkad, Alappuzha, Kottayam, and Pathanamthitta, in the lower quartile showed a difference in precipitation of about -0.8 kg/m^2 .

Relative humidity exhibited positive differences in the upper and lower parts of Kerala. This implies that relative humidity has increased in these regions during period 2. The maximum temperature increased in the northern part, and the mean temperature decreased significantly in the southern part of Kerala for both quartiles for Period 2.

In Kannur and areas of Malappuram, Ernakulam, Kottayam, and Alappuzha during the Kharif season, the relative humidity is the same for both quartiles, as shown in Fig. 9. In the two quartiles, in the regions of Kasaragod and Thiruvananthapuram, the differences obtained were the same, indicating that the maximum temperature for regions having low and high values has not changed over time. During Kharif, the mean temperature is approximately the same in Kasaragod for both quartiles. Throughout Kerala, all the districts observed a negative difference in both tails for mean temperature. Precipitation in the upper quartile is greater than -2 kg/m^2 in Thiruvananthapuram, Kollam,

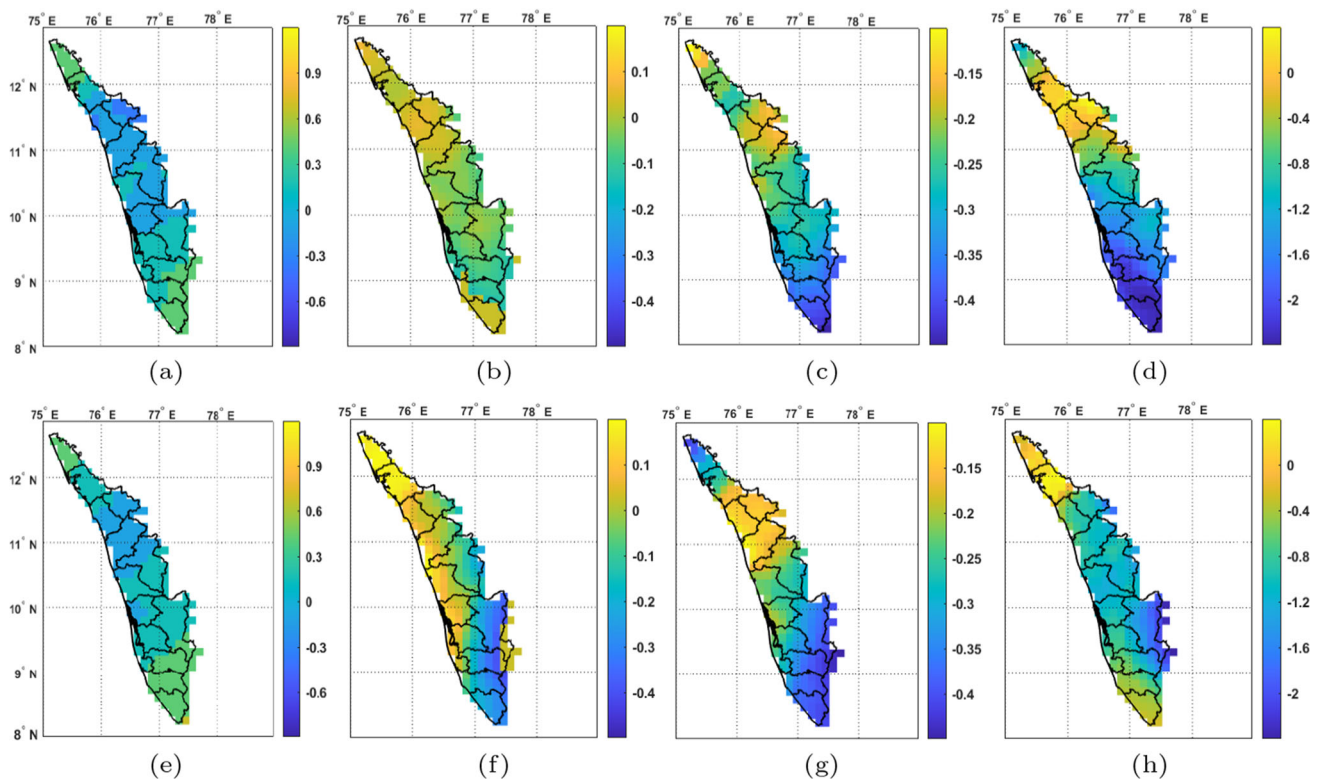


Fig. 8 Annual tail diagnostics - upper quartile (a) relative humidity, (b) maximum temperature, (c) mean temperature, and (d) precipitation; lower quartile (e) relative humidity, (f) maximum temperature, (g) mean temperature, and (h) precipitation

Alappuzha, and portions of Pathanamthitta. However, for the lower quartile, a similar disparity is visible in some regions of Idukki. Parts of Kozhikode, Wayanad, and Malappuram experienced the same relative humidity differences in both quartiles (-0.6%) during the Rabi season. Since the relative humidity showed no differences in the regions of Alappuzha, Pathanamthitta, Kollam, and Thiruvananthapuram, the lower tails are the same for both periods. The spatial images of the maximum temperature for both quartiles were virtually similar. Thiruvananthapuram and some regions of Kollam have

mean temperatures of $-0.4K$ in the upper quartile, whereas Thiruvananthapuram, Kollam, and portions of Pathanamthitta and Idukki have mean temperatures greater than $-0.4K$ in the lower quartile. For precipitation during Rabi, in the upper quartiles of Alappuzha, parts of Thiruvananthapuram, Ernakulam, and Kottayam recorded no difference. The same is observed in the regions of Kollam, Alappuzha, and Pathanamthitta in the lower tail. In some areas of Idukki during Zaid, the relative humidity difference in the upper tail is zero percent. Both quartiles have positive relative humidity

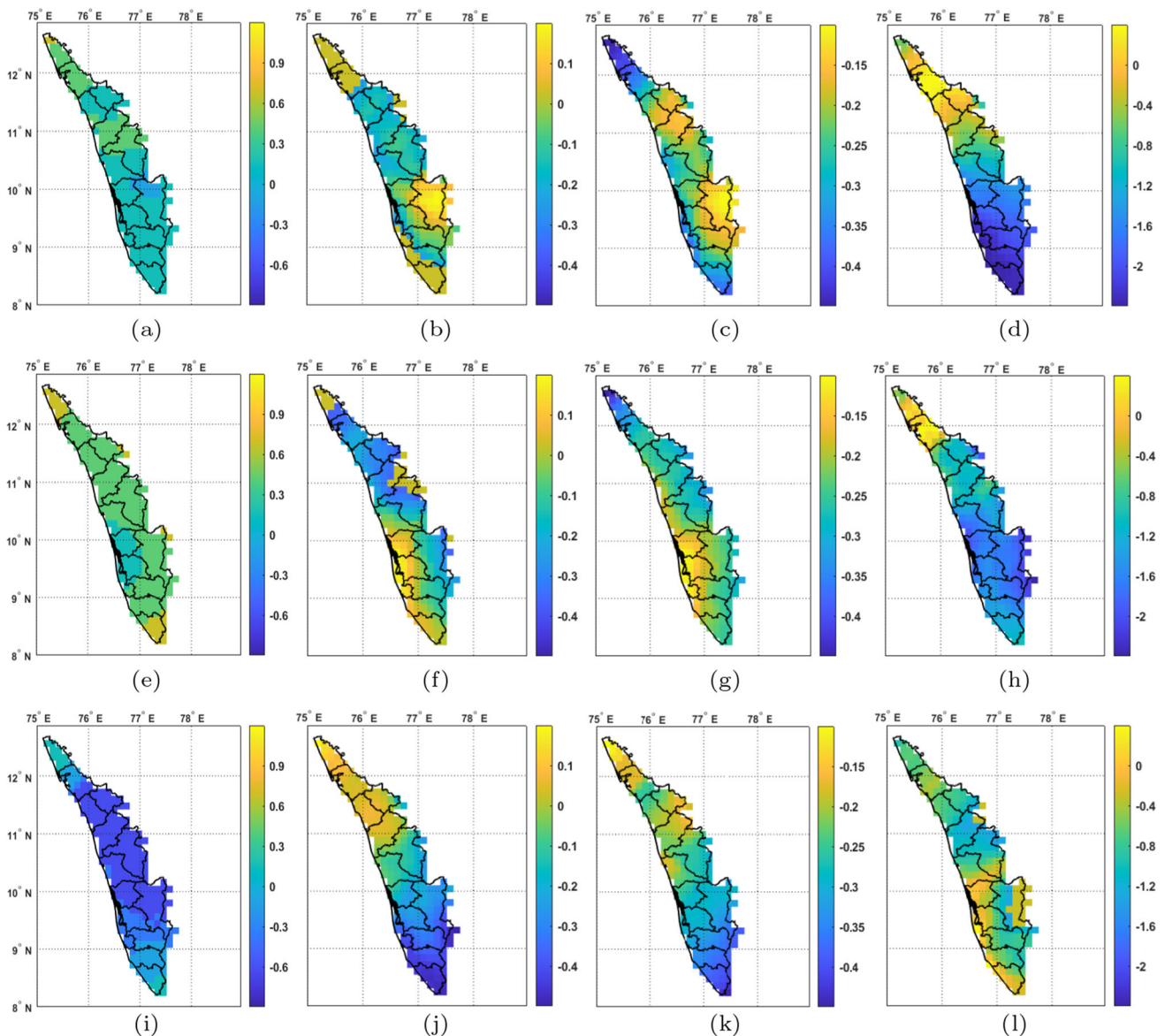


Fig. 9 Seasonal tail diagnostics: Kharif-upper quartile (a) relative humidity, (b) maximum temperature, (c) mean temperature, and (d) precipitation, lower quartile (e) relative humidity, (f) maximum temperature, (g) mean temperature, and (h) precipitation; Zaid-upper quartile (i) relative humidity, (j) maximum temperature, (k) mean temperature,

and l precipitation, lower quartile (m) relative humidity, (n) maximum temperature, (o) mean temperature, and (p) precipitation; Rabi-upper quartile (q) relative humidity, (r) maximum temperature, (s) mean temperature, and (t) precipitation, lower quartile (u) relative humidity, (v) maximum temperature, (w) mean temperature, and (x) precipitation

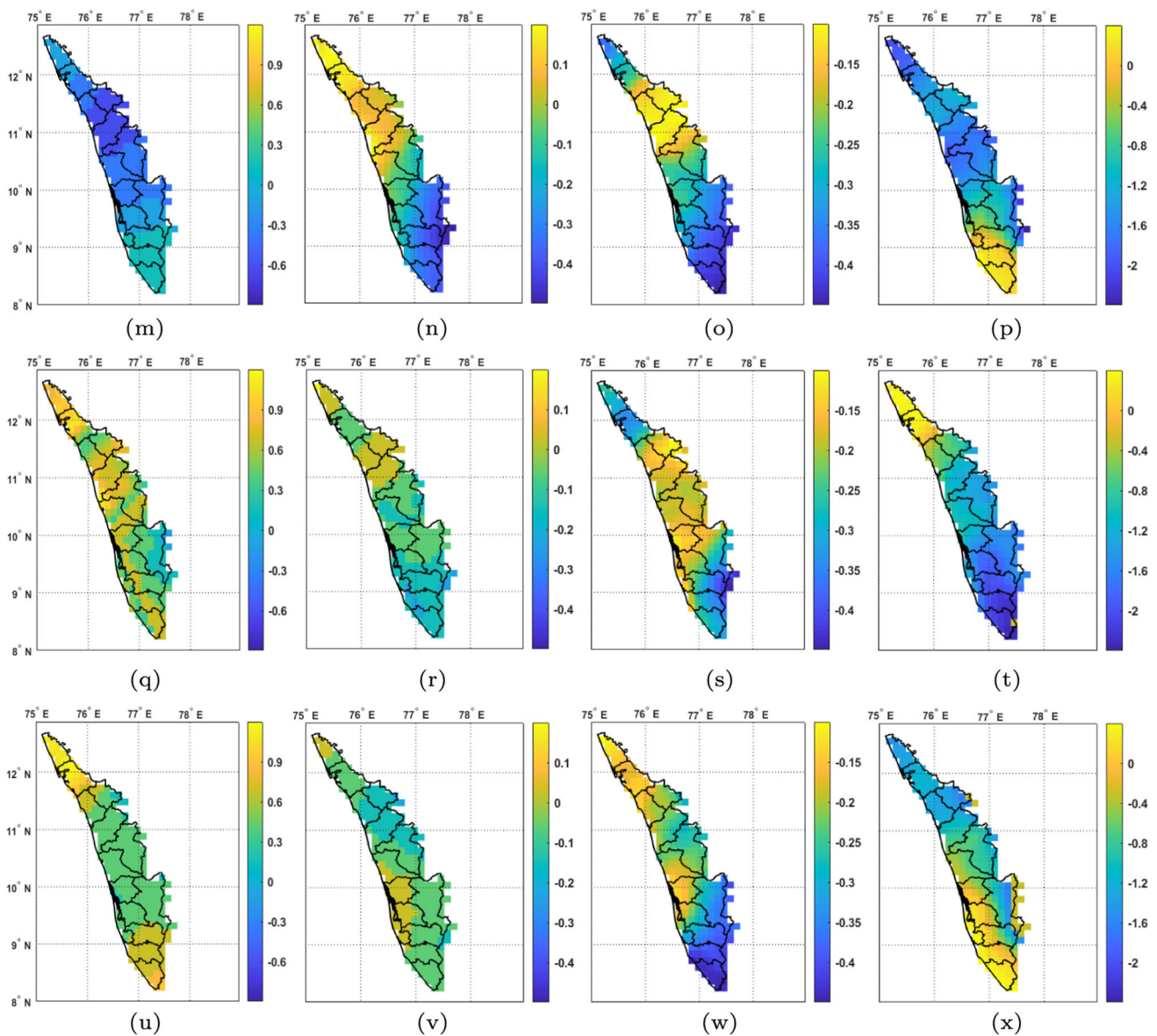


Fig. 9 continued

differences. The maximum temperature changes observed in the parts of Kasaragod, Kannur, and Idukki are nearly the same during the Zaid season in both tails. The mean temperature ($-0.15K$) in Kozhikode, Wayanad, Ernakulam, and in some areas of Malappuram, Thrissur, Palakkad, Idukki, Kottayam and Alappuzha in the upper quartile and Kasaragod, Kannur, Ernakulam, and regions of Kozhikode, Thrissur, and Kottayam in the lower quartile is the same. The lower tail difference for some areas of Kasaragod, Ernakulam, Kottayam, and Alappuzha recorded positive maximum temperature. Positive difference in precipitation was found in Kasaragod

and Kannur, in the upper quartile, and in Thiruvananthapuram, Kollam, Alappuzha, Kottayam, and some parts of Pathanamthitta and Ernakulam, in the lower quartile.

Areas of Idukki witnessed an increase in relative humidity during Kharif in period 2, while mean temperature and precipitation levels fell. Relative humidity in Thiruvananthapuram and Kasaragod showed no differences from one another in Rabi. In every region throughout Zaid, relative humidity increased in period 2. In the same period, Kasaragod experienced higher maximum temperature readings.

3.3.2 Maximum areal difference

The relative humidity in Thiruvananthapuram, Kollam, Pathanamthitta, Idukki, and Ernakulam varied by zero percent. While it is evident from Fig. 10 that a difference of 0.3 % was observed in Kasaragod, some areas of Kannur, Thrissur, Palakkad, Alappuzha, and Kottayam. The maximum temperature differences in the Kozhikode, Wayanad, and Idukki regions recorded a value of 0.1 K, whereas Kerala as a whole showed negative differences in mean temperature. There wasn't any difference in precipitation in certain areas of Kannur, Kozhikode, Wayanad, Malappuram, and Palakkad.

Periods 1 and 2 with normal relative humidity displayed the same values throughout Kerala. The maximum temperature in the majority of Kerala showed a positive difference, indicating that maximum temperature values have increased. However, mean temperature values have decreased over time. Except for Wayanad, period 2 observed a decline in precipitation. According to research by Sethi et al. (2022), this validates our findings.

During Kharif, there were no variations in relative humidity for both the periods in Kasaragod, Kannur, Kozhikode, Thrissur, Ernakulam, Kottayam, Alappuzha, and in the regions of Wayanad, Malappuram, Palakkad, Idukki, and Pathanamthitta. Figure 11 refers to this observation. Certain regions in Kannur, Thrissur, Ernakulam, Kottayam, Alappuzha, Kollam, and Thiruvananthapuram also experienced the same during Rabi. Parts of Thiruvananthapuram, Kollam, Pathanamthitta, Kottayam, and Idukki showed no difference in humidity during Zaid. Idukki recorded its maximum temperature difference during Kharif (which is greater than 0.1 K), while Kerala as a whole recorded negative mean temperatures. Parts of Kasaragod, Idukki, and the borders of Kozhikode and Wayanad experienced a maximum temperature difference of 0.1 K during the season of Rabi. In

some areas of Kasaragod, the seasonal difference in mean temperature recorded a value of -0.15 K. Zaid exhibited a maximum temperature difference of 0.1 K in areas of Wayanad, while the mean temperature across Kerala depicted negative readings. Precipitation in Kharif showed no difference in some areas of Kannur, Kozhikode, and Wayanad. However, in Rabi, areas of Thrissur, Palakkad, Ernakulam, and Alappuzha experienced zero variations. On the borders of Kannur, Kozhikode, and Wayanad, no difference in precipitation amounts were observed during Zaid.

Season Kharif observed a decrease in values for the second period for the zones with normal relative humidity. The values also decreased for Rabi, except Kasaragod and several areas of Kannur, and during Zaid, values increased in period 2 except for several areas in Idukki, Pathanamthitta, and Kollam. During the seasons of Kharif and Rabi, Idukki noticed a pattern. In other words, a rise in relative humidity and precipitation during period 1 was linked to a decline in maximum temperature, whereas a decline in relative humidity and precipitation during period 2 was linked to an increase in maximum temperature. During Zaid, Kasaragod, and Kannur exhibited the same phenomenon. Period 2 in Zaid exhibited a decline in precipitation when Idukki recorded both positive and negative readings for temperature and humidity.

Table 2 depicts the overall summary of annual and seasonal inter vicennial variations in climatic variables at the 234 grid points over Kerala.

It can be noticed that maximum positive change is seen in the mean temperature where all gridpoints depict an increase in annual and Kharif season whereas maximum negative can be noticed for relative humidity for the Rabi season. The upper and lower tail diagnostic suggest a decrease in all gridpoints for all the parameters (except relative humidity) on an annual and seasonal scale (except Zaid). Results from maximum areal difference depict significant changes for relative humidity, mean temperature and precipitation.

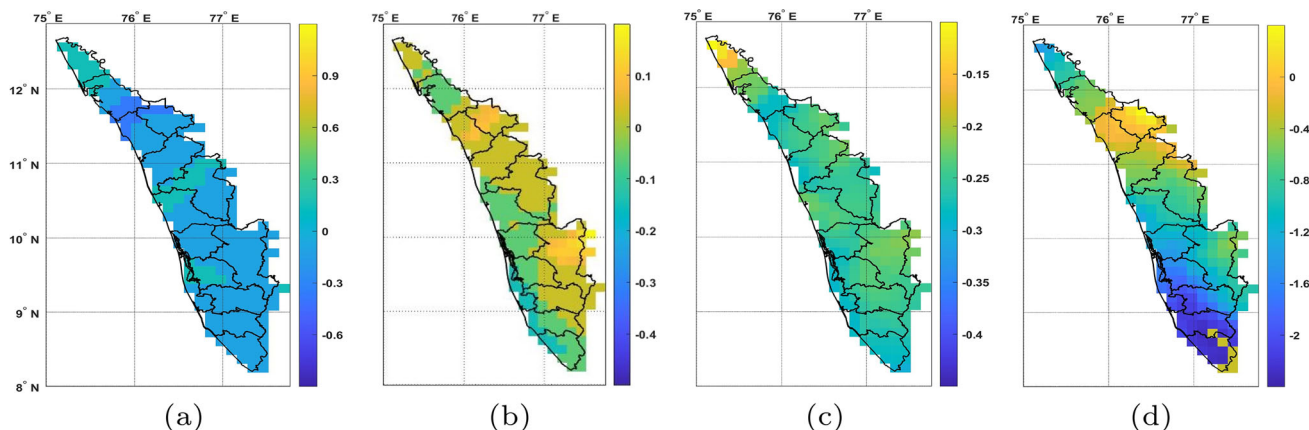


Fig. 10 Annual maximum areal difference: (a) relative humidity, (b) maximum temperature, (c) mean temperature, and (d) precipitation

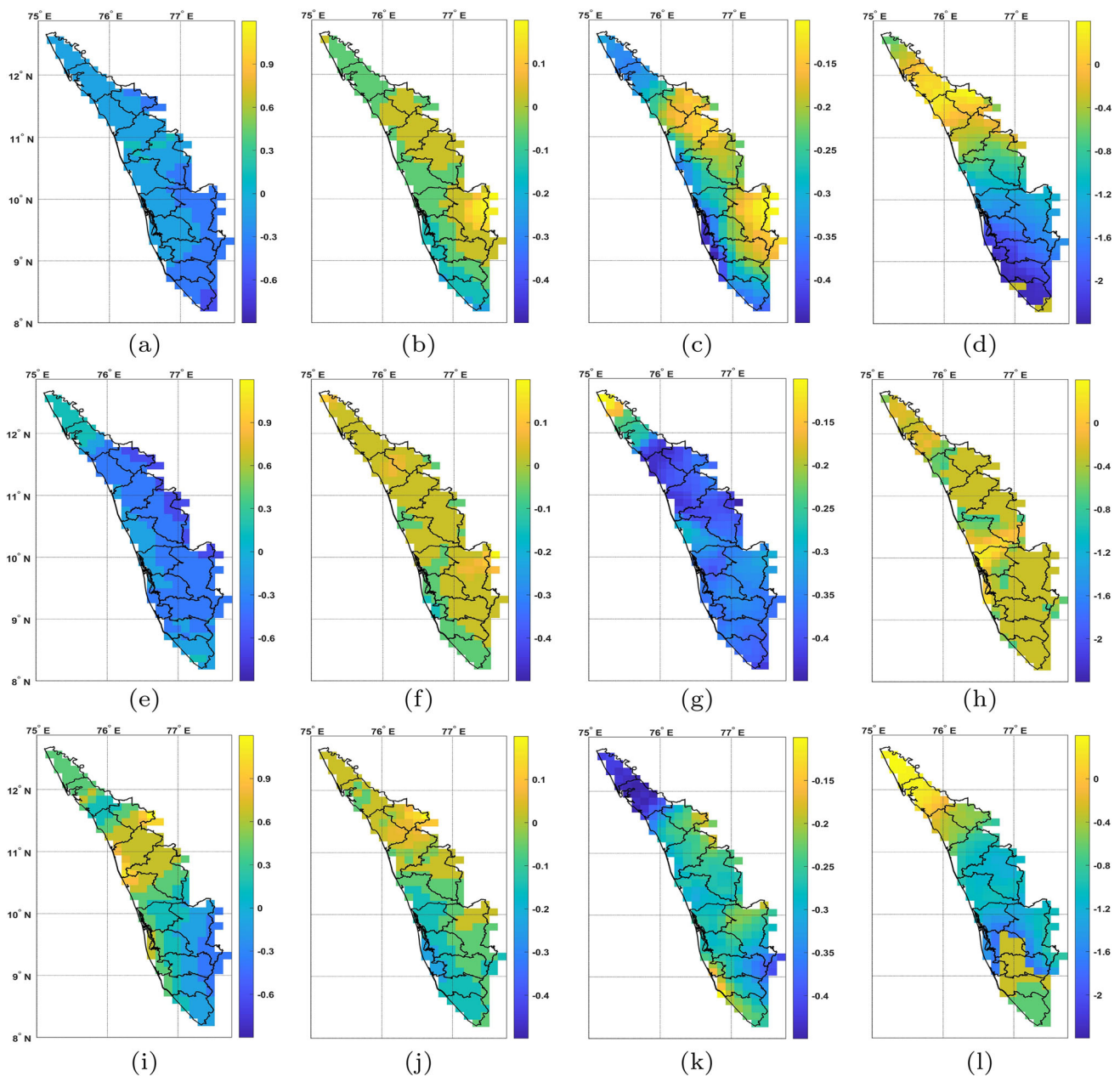


Fig. 11 Seasonal maximum areal difference: Kharif (a) relative humidity, (b) maximum temperature, (c) mean temperature, and (d) precipitation; Zaid (i) relative humidity, (j) maximum temperature, (g) mean

temperature, and (h) precipitation; Rabi (i) relative humidity, (j) maximum temperature, (k) mean temperature, and (l) precipitation

3.4 Inter-decadal changes

In the following section, three time periods (period 1, period 2, and period 3) are considered to analyse the decadal changes in the climate variables. Period 1: difference of the years 1980–1990 from 1991 to 2000; period 2: difference of 1991–2000 from 2001 to 2010; and period 3: difference of 2001–2010 from 2011 to 2020.

Relative humidity difference declined (-0.3%) in certain places in Thrissur, Alappuzha, Wayanad, Kozhikode, and Kollam during period 1 as shown in Fig. 12. In some areas of Idukki, Alappuzha, Thrissur, Kollam, Kozhikode, Kannur, Wayanad, Malappuram, and Palakkad, the maximum temperatures difference were recorded between -0.1 and -0.3 K. Mean temperature and precipitation at the time period 1991–2000 decreased when compared to 1980–1990. The

Table 2 Annual and seasonal inter-vicennial changes in the grid points of Kerala (in percentage)

Inter-vicennial difference	Grid point nature	Annual (%)	Kharif (%)	Rabi (%)	Zaid (%)
Relative humidity	Positive	70	99.57	21.79	98.72
Relative humidity	Negative	30	0.43	78.21	1.28
Maximum temperature	Positive	99	96.15	56.41	32.05
Maximum temperature	Negative	1	38.5	43.59	67.95
Mean temperature	Positive	100	100	90.17	91.45
Mean temperature	Negative	0	0	9.83	8.55
Precipitation	Positive	98.29	97.86	36.75	91.03
Precipitation	Negative	1.71	2.24	63.25	8.97
Upper tail diagnostics					
Relative humidity	Positive	47.44	5.13	92.74	1.28
Relative humidity	Negative	52.56	94.87	7.26	98.72
Maximum temperature	Positive	0	0	0	79.49
Maximum temperature	Negative	100	100	100	20.51
Mean temperature	Positive	0	0	0	2.56
Mean temperature	Negative	100	100	100	97.44
Precipitation	Positive	0	0	8.12	0.43
Precipitation	Negative	100	100	91.88	99.57
Lower tail diagnostics					
Relative humidity	Positive	27.35	0	78.21	0
Relative humidity	Negative	72.65	100	21.79	100
Maximum temperature	Positive	0	0	0	82.05
Maximum temperature	Negative	100	100	100	17.95
Mean temperature	Positive	0	0	0	0.43
Mean temperature	Negative	100	100	100	99.57
Precipitation	Positive	0	0	0	6.41
Precipitation	Negative	100	100	100	93.59
Maximum areal difference					
Relative humidity	Positive	17.09	2.99	8.55	71.79
Relative humidity	Negative	82.91	97.01	91.45	28.21
Maximum temperature	Positive	62.39	45.73	77.78	41.03
Maximum temperature	Negative	37.61	54.27	22.22	58.97
Mean temperature	Positive	82.91	48.72	91.03	82.05
Mean temperature	Negative	17.09	51.28	8.97	17.95
Precipitation	Positive	97.44	97.86	41.45	79.06
Precipitation	Negative	2.56	2.14	58.55	20.94

highest negative relative humidity difference (-0.6%) was recorded during period 2 in the Wayanad district, as well as in parts of Malappuram, Kozhikode, Palakkad, Ernakulam, and Idukki. The places with the highest maximum temperature differences (-0.4 K) during this time period were observed in Wayanad, Palakkad, and Idukki, as well as certain regions of Kozhikode, Malappuram, Thrissur, Ernakulam, Kottayam, and Pathanamthitta. Precipitation did not differ significantly in this period. During period 3, there were no variations in humidity in Kasaragod and regions of Malappuram. Its difference fluctuated between 0.3 and 0.6% in the districts

of Kozhikode, Kannur, Thrissur, Thiruvananthapuram, and some parts of Palakkad, Alappuzha, Ernakulam, and Idukki. Parts of Wayanad, Malappuram, and Idukki showed positive differences in maximum temperature.

Relative humidity showed positive variations in periods 1 and 3 but negative variations in most of Kerala in period 2. Period 2 witnessed no difference in Thiruvananthapuram. The maximum temperature difference in Period 1 marginally fluctuated in positive and negative directions. There was a significant negative difference in period 2 except for Kasaragod and Thiruvananthapuram. The difference in the temperature

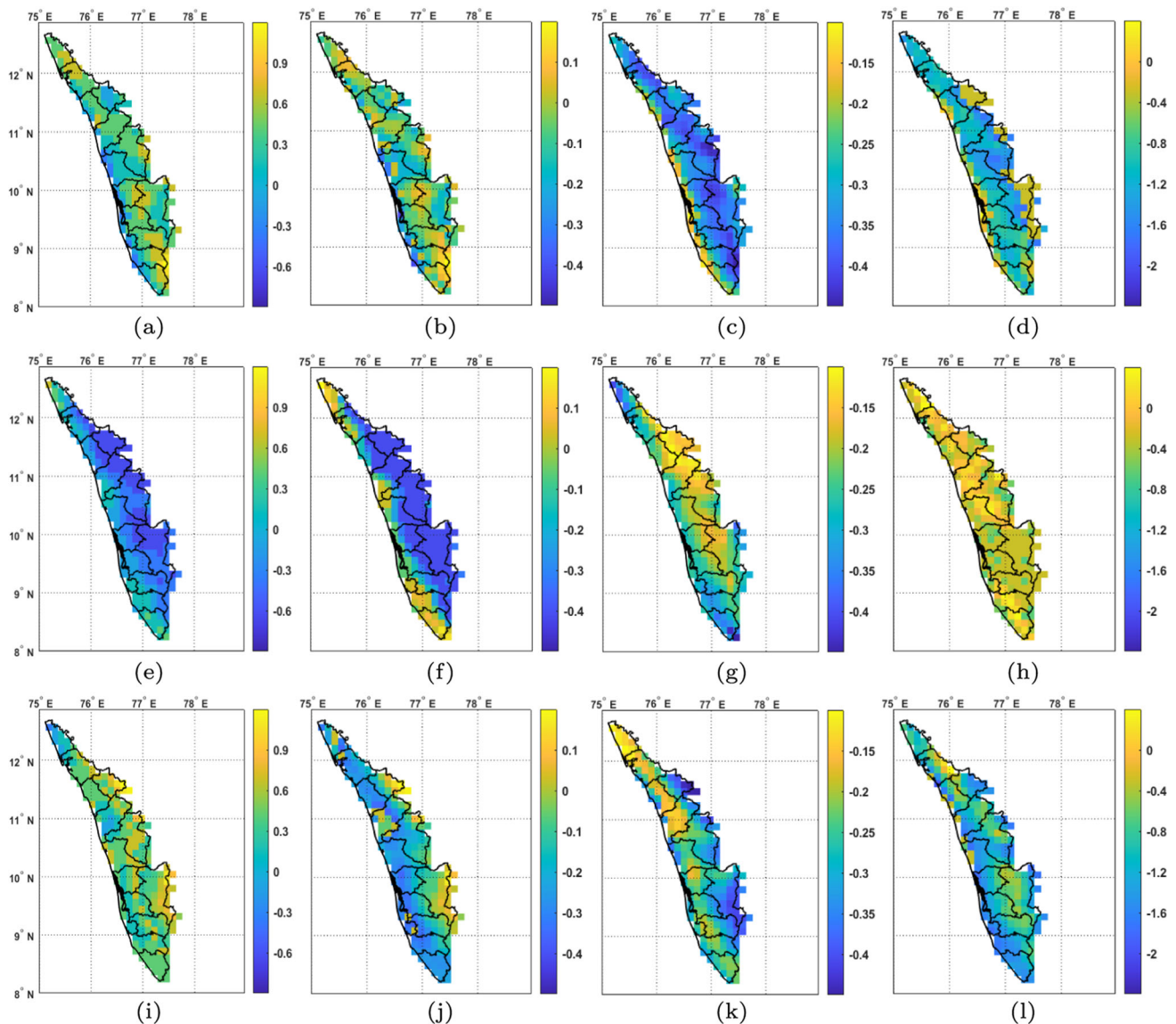


Fig. 12 Annual inter decadal difference: Period 1 (a) relative humidity, (b) maximum temperature, (c) mean temperature, and (d) precipitation; Period 2 (e) relative humidity, (f) maximum temperature, (g) mean

temperature, and (h) precipitation; Period 3 (i) relative humidity, (j) maximum temperature, (k) mean temperature, and (l) precipitation

dropped across the board in period 3, except for a few areas in Idukki and Wayanad. Kerala experienced negative mean temperature differences for all three periods. Kasaragod observed a difference of -0.15 K in the average temperature in period 3. Difference in precipitation is observed as negative throughout Kerala for periods 1 and 3.

In some parts of Thiruvananthapuram, Kollam, and Pathanamthitta during period 1 of Kharif, the difference in relative humidity ranged from 0.6 to 0.9% (Fig. 13). Maximum temperature differences of -0.1 K were recorded in some areas of Pathanamthitta, Kollam, and Thiruvananthapuram. In this time frame, Thiruvananthapuram, Kollam,

Pathanamthitta, Kottayam, and some areas of Idukki, Ernakulam, and Kannur experienced differences in precipitation ranging from -0.5 to -1.6 kg/m^2 . Kasaragod has the highest positive relative humidity difference during period 2. In several areas of Thiruvananthapuram, Kollam, Alappuzha, Kottayam, Ernakulam, Thrissur, Malappuram, Kozhikode, and Kannur, the difference in maximum temperature of -0.1 K was recorded. In several areas of Kasaragod, the mean temperature variations were extremely negative. Malappuram reported no variations in precipitation, and parts of Kasaragod recorded positive differences. In the districts of Thiruvananthapuram and Kannur, the humidity during period 3 exhibited no variations.

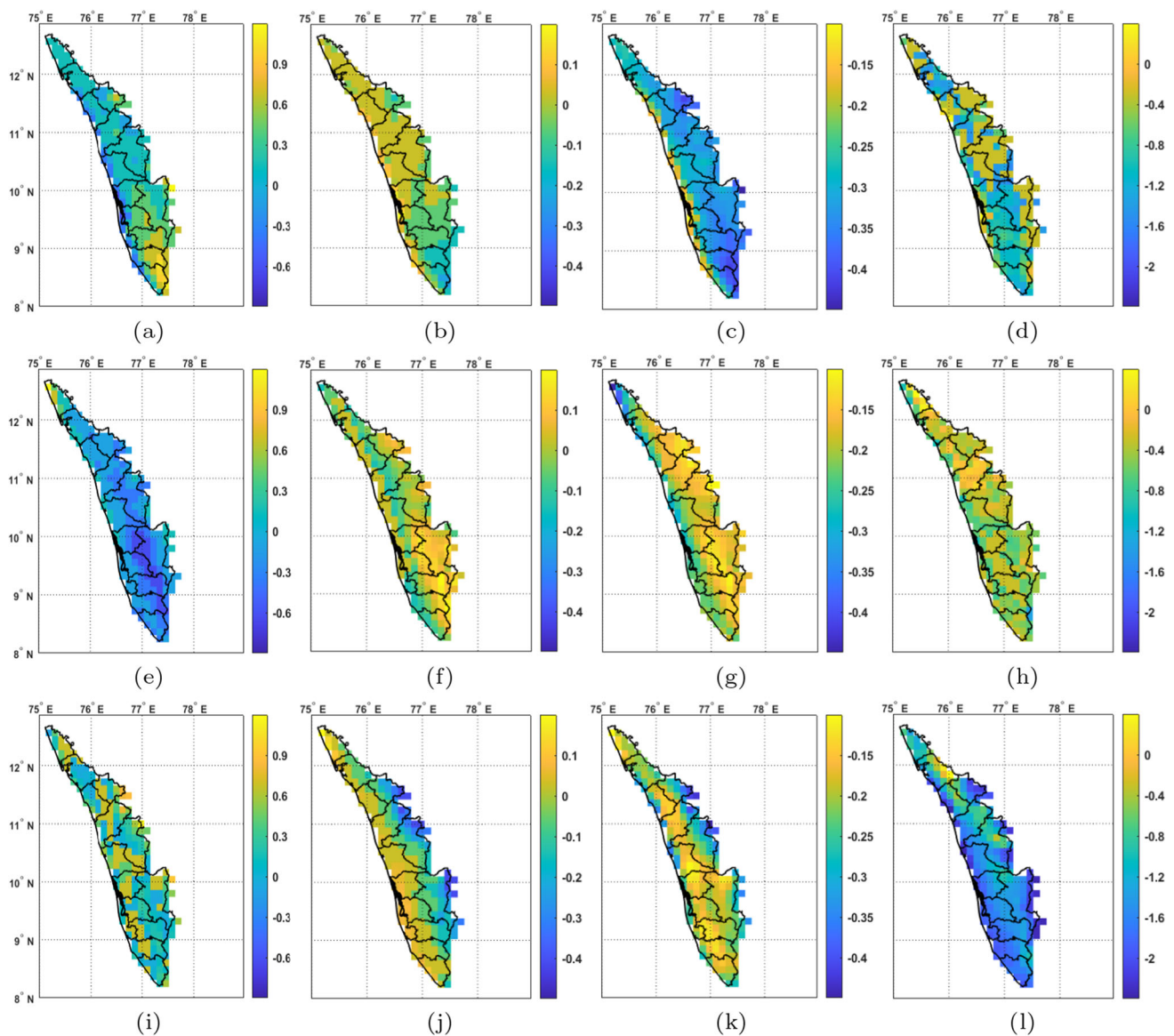


Fig. 13 Seasonal inter decadal difference for Kharif: Period 1 (a) relative humidity, (b) maximum temperature, (c) mean temperature, and (d) precipitation; Period 2 (e) relative humidity, (f) maximum temper-

ature, (g) mean temperature, and (h) precipitation; Period 3 (i) relative humidity, (j) maximum temperature, (k) mean temperature, and (l) precipitation

In Kharif, most areas of Kerala witnessed positive humidity differences throughout periods 1 and 3. In period 2, the variations in humidity did not significantly change. The northern region of Kerala in period 1, the southern part in period 2, and the coastal parts in period 3 all exhibited positive differences in maximum temperature. In Kerala, the highest mean temperature differences were marked in period 1. Precipitation and mean temperature showed negative changes throughout period 3, while relative humidity showed positive shifts.

In Thiruvananthapuram, Kollam, Alappuzha, Malappuram, and Wayanad in period 1 of Rabi, relative humidity

did not vary (figure not shown). In Pathanamthitta, Kottayam, Idukki, Ernakulam, Thrissur, Palakkad, and in areas of Thiruvananthapuram, Kollam, and Malappuram districts, the maximum temperature difference was extremely negative ($-0.4 K$). The same mean temperature was reported in parts of Pathanamthitta, Idukki, Wayanad, Thrissur, Kottayam, and Palakkad. Differences in precipitation of about $-0.8 kg/m^2$ were witnessed in the districts of Kasaragod, Kannur, and Thiruvananthapuram. Alappuzha, Kottayam, Ernakulam, Thrissur, Palakkad, Malappuram, Kozhikode, Wayanad, and Kannur districts experienced a difference in humidity of -0.6% during period 2. Positive fluctuations in maximum

temperature differences were seen in Kottayam, Ernakulam, Thrissur, and in the regions of Alappuzha, Idukki, Palakkad, Malappuram, Kozhikode, Wayanad, Kannur, and Kasaragod. In some areas of Kozhikode, Wayanad, Thrissur, and Idukki, there were significant changes in the amount of precipitation (-2 kg/m^2). In period 3, Kasaragod, Kannur, Kozhikode, and a few areas in Malappuram and Thrissur all exhibited positive humidity differences. Maximum temperature differences in some regions of Thiruvananthapuram, Kollam, and Pathanamthitta increased.

Kerala's humidity in period one during Rabi differed positively in the majority of the regions when compared to other periods. During the same period, Kerala's southern and central parts showed significant negative differences in the maximum temperature. Compared to periods 1 and 3, the mean temperature over Kerala in period 2 showed marginal variations.

Parts of Malappuram, Thrissur, Palakkad, Ernakulam, Idukki, Kottayam, Pathanamthitta, and Kollam reported high positive humidity differences (0.9 %) during the season of Zaid in period 1 (figure not shown). Mean temperature observed negative differences of -0.4 K in regions of Malappuram, Thrissur, Palakkad, Ernakulam, Kottayam, Idukki, Pathanamthitta, and Kollam. In some areas of Wayanad, Palakkad, and Idukki, the variation in precipitation was significant (-2 kg/m^2). In period 2, the relative humidity in the districts of Kasaragod, Kannur, Kozhikode, Thiruvananthapuram, and Kollam, and some regions of Thrissur, Malappuram, and Alappuzha varied from 0.3 to 0.9%. No significant positive differences in maximum temperature were observed. A mean temperature difference of -0.15 K was recorded in parts of Palakkad, Ernakulam, Kottayam, and Idukki. In the regions of Idukki and Pathanamthitta, precipitation showed severe disparities (-1.2 kg/m^2). Many areas, including Kasaragod, Kannur, Kozhikode, Malappuram, Thrissur, Palakkad, Ernakulam, Kottayam, Idukki, Pathanamthitta, Kollam, and Thiruvananthapuram, experienced positive differences in maximum temperatures for period 3. Precipitation at this time showed no variations in various regions of Idukki and Pathanamthitta.

During Zaid, humidity in period 3 experienced high negative differences comparatively. Compared to the other two periods, Kerala experienced greater maximum temperature variations (-0.4 K) during period 1. Throughout this time, the majority of Kerala experienced a significant decrease in the mean temperature and precipitation differences.

3.4.1 The tail diagnostics

All regions in the upper quartile of humidity during period 1 exhibited no difference, except for Kasaragod, Kannur, Ernakulam, Kollam, and Thiruvananthapuram, as shown in Fig. 14. The difference throughout Kerala was positive in

the lower tail. In the upper tail, the districts of Thiruvananthapuram and Alappuzha and some parts of Kollam and Thrissur reported a maximum temperature difference that was extremely negative (-0.4 K). However, in the lower tail, every district recorded a temperature difference of -0.1 K except Alappuzha. The upper tail difference of the mean temperature recorded values higher than -0.4 K in several areas of Idukki. The case is the same in Kasaragod and Kannur in the lower tail. Precipitation showed no variations in parts of Alappuzha, Ernakulam, Kottayam, Pathanamthitta, and Kollam in the lower tail. Kasaragod showed no variation in humidity during period 2 in any of the quartiles. In the upper tail, Kasaragod, Kannur, Kozhikode, Wayanad, and some areas of Thrissur, Ernakulam, and Idukki experienced positive differences in maximum temperature. Meanwhile, Malappuram, Kozhikode, Wayanad, Kannur, and regions of Kasaragod reported positive variations in the lower tail. Regions with high and low values for the mean temperature difference declined over time. The lower tail of precipitation in Thiruvananthapuram and the upper tail in Kasaragod, Kannur, Kozhikode, and Wayanad both showed a positive difference.

Pathanamthitta, as well as the areas of Idukki, Kottayam, and Alappuzha, experienced a relative humidity difference of 0.9 % in the upper tail during period 3. A maximum temperature difference of 0.1 K was observed in the upper quartile for Kozhikode, Wayanad, Malappuram, and Palakkad. In the lower quartile, Kasaragod and Thrissur recorded the same temperature. The amount of precipitation in the upper tail did not differ in the Kottayam, Idukki, Kozhikode, Wayanad, and Kannur regions. The same is true in the lower tail for several places in Kasaragod and Kannur.

The relative humidity differences in the two tails of period 2 of the yearly data were negative in most districts. During the same time span, both quartiles of maximum temperature exhibited positive changes in Kerala's northern region and adverse variations in its southern region. The upper and lower tails of the mean temperature difference in Kasaragod were reported to have the same value in period 3.

In the district of Wayanad and parts of Kasaragod, Kozhikode, Malappuram, and Palakkad during Kharif, no variations were observed in the upper quartile of humidity (Fig. 15). In the lower tail, Thiruvananthapuram and some areas in Kollam and Pathanamthitta exhibited high positive differences. High negative deviations in the upper tails of the maximum temperature (-0.4 K) were observed in Thiruvananthapuram, Kollam, and Alappuzha. The lower quartile showed positive changes in the districts of Kasaragod, Kannur, Kozhikode, Wayanad, Malappuram, Thrissur, Palakkad, Ernakulam, Kottayam, Idukki, and Alappuzha. Kozhikode, Wayanad, and areas of Malappuram, Idukki, Pathanamthitta, Kollam, and Thiruvananthapuram recorded a mean temperature of -0.4 K in the lower tails during this time period.

Kannur, Ernakulam, and parts of Kasaragod, Thrissur, and Palakkad experienced negative differences in precipitation (-2 kg/m^2) in the upper tail. The districts of Kozhikode and Wayanad in both tails did not exhibit any changes in humidity during period 2. Positive disparities in the maximum temperature were observed at the upper and lower quartiles in Idukki. Precipitation in the districts of Kasaragod and Kannur showed positive differences in the upper tail. Highly positive differences in the upper tail of maximum temperature were

observed in Kasaragod during period 3. However, this district had the least variations in mean temperature.

Period 3 of Kharif witnessed positive changes in humidity across the entire state of Kerala, while period 2 observed negative differences in the southern regions of Kerala in both tails. For maximum temperature during period 1, most of the regions exhibited negative differences in the upper quartile and positive differences in the lower quartile. In Kasaragod, the lower tail of the precipitation during period 3 revealed no differences.

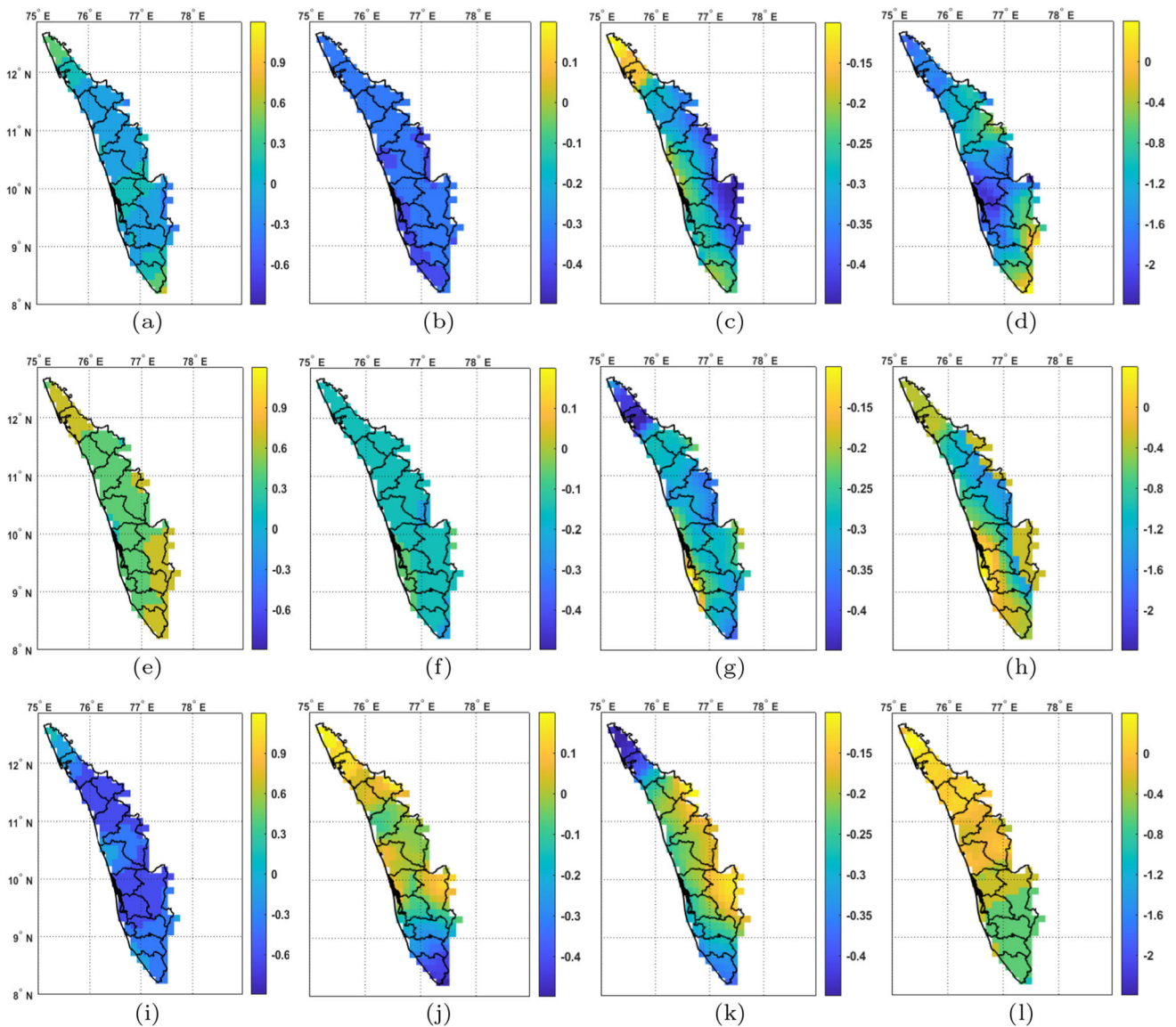


Fig. 14 Annual tail diagnostics: Period 1-upper quartile (a) relative humidity, (b) maximum temperature, (c) mean temperature, and (d) precipitation, lower quartile (e) relative humidity, (f) maximum temperature, (g) mean temperature, and (h) precipitation; Period 2-upper quartile (i) relative humidity, (j) maximum temperature, (k) mean temperature, and (l) precipitation, lower quartile (m) relative humidity, (n)

maximum temperature, (o) mean temperature, and (p) precipitation; period 3-upper quartile (q) relative humidity, (r) maximum temperature, (s) mean temperature, and (t) precipitation, lower quartile (u) relative humidity, (v) maximum temperature, (w) mean temperature, and (x) precipitation

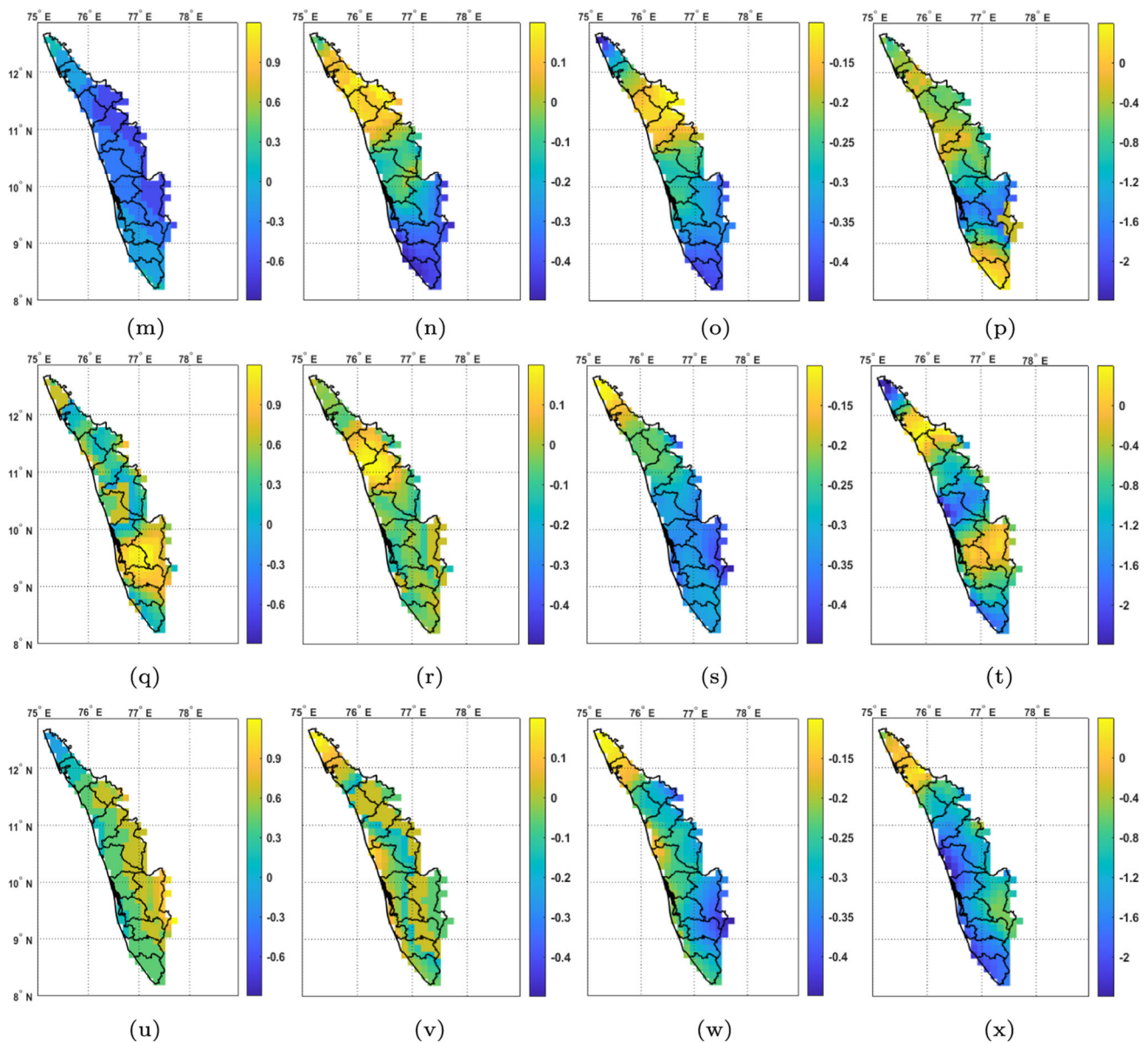


Fig. 14 continued

Kasaragod recorded positive changes in the upper tail of humidity during Rabi in period 1, whilst the other regions showed negative differences (figure not shown). The districts of Kasaragod, Kannur, Kozhikode, and Wayanad, as well as the regions of Malappuram and Palakkad, experienced differences in humidity levels between 0.6 and 0.9% in the lower tail. High negative differences (-0.4 K) in the upper tail of the maximum temperature were observed in the districts of Kasaragod, Kannur, Kozhikode, Wayanad, Thrissur, and Palakkad. In the lower quartile, the mean temperature difference ranged between -0.2 and -0.15 K in the districts of Kozhikode, Wayanad, Malappuram, Alappuzha, Kottayam, Idukki, Pathanamthitta, Kollam, and Thiruvananthapuram. Positive variations in precipitation were observed

in Kasaragod in the upper tail and Malappuram in the lower tail. In Kasaragod and several areas of Kannur and Thrissur in the upper quartile during period 2, no variations in humidity were recorded. In the lower quartile, a humidity difference of -0.6% was recorded in the districts of Kannur, Kozhikode, Wayanad, Malappuram, Thrissur, Palakkad, Ernakulam, Kottayam, Idukki, and some parts of Pathanamthitta.

In the districts of Kasaragod and Kannur, the maximum temperatures during this time period showed positive differences in both tails. Idukki, in the upper quartile, and Kozhikode, Wayanad, and Malappuram, in the lower quartile, recorded a mean temperature difference of -0.15 K . Positive changes were evident in the lower tails of the precipitation in the districts of Thiruvananthapuram and Kollam.

The humidity for both quartiles varied significantly in some areas of Idukki throughout period 3. Positive differences were observed in the upper tail of maximum temperature in Kozhikode, Wayanad, and Malappuram. The same is true for Kasaragod in the lower tail. For mean temperature, differences obtained in both tails were identical. Positive differences were observed in Alappuzha, Idukki, Kottayam, Pathanamthitta, and Kollam in the upper quartile of precipitation and Idukki in the lower quartile.

Throughout the rabi season, there were negative changes in the lower quartile for humidity in period 2. Negative fluctuations were also noted in the upper tail, excluding the regions of Kasaragod, Kannur, and Thrissur. For period 2, the maximum temperature differences in the districts of Pathanamthitta, Thiruvananthapuram, and Alappuzha are the same in both tails. The upper tail of the precipitation at Kasaragod during Period 1 exhibited positive differences.

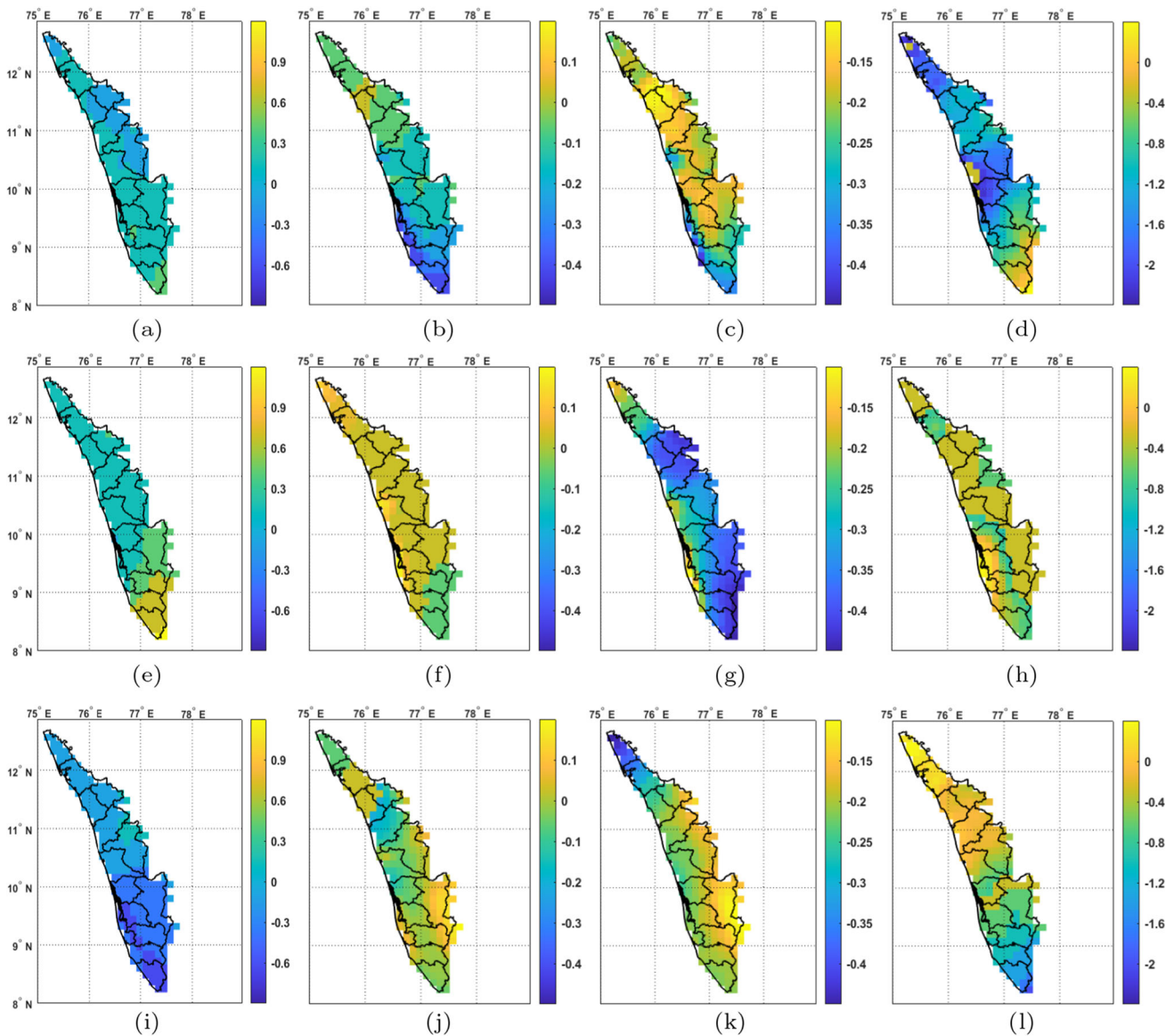


Fig. 15 Seasonal tail diagnostics for Kharif: Period 1-upper quartile (a) relative humidity, (b) maximum temperature, (c) mean temperature, and (d) precipitation, lower quartile (e) relative humidity, (f) maximum temperature, (g) mean temperature, and (h) precipitation; Period 2-upper quartile (i) relative humidity, (j) maximum temperature, (k) mean temperature, and (l) precipitation, lower quartile (m) relative humidity, (n)

maximum temperature, (o) mean temperature, and (p) precipitation; Period 3-upper quartile (q) relative humidity, (r) maximum temperature, (s) mean temperature, and (t) precipitation, lower quartile (u) relative humidity, (v) maximum temperature, (w) mean temperature, and (x) precipitation

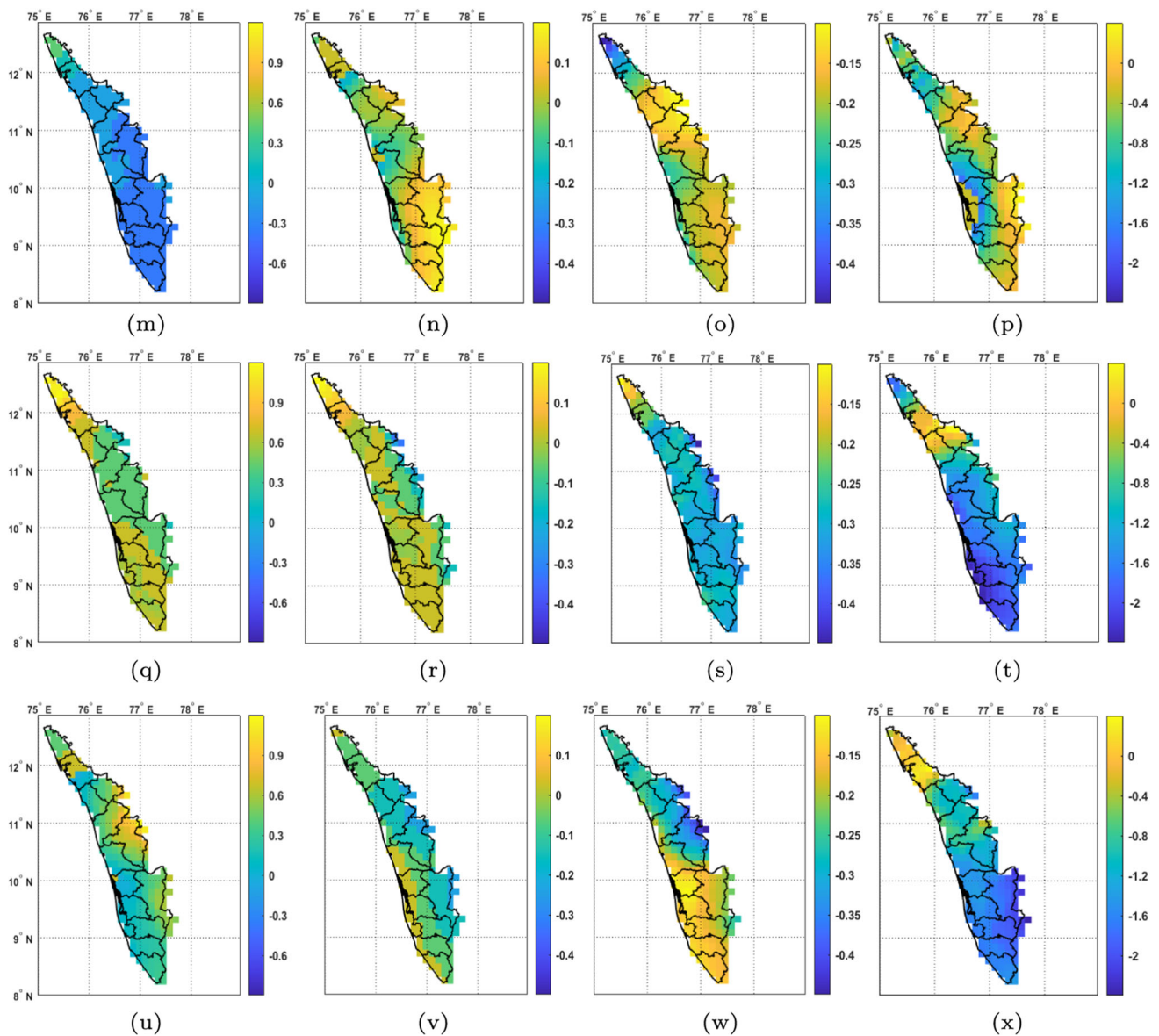


Fig. 15 continued

In the lower quartile difference during Zaid in period 1, relative humidity values higher than 0.6 % was observed in the districts of Kasaragod and in the regions of Kannur (figure not shown). Idukki, which is in the upper quartile of mean temperature, and Thrissur, Palakkad, Ernakulam, Alappuzha, Kottayam, Idukki, Pathanamthitta, Kollam, and Thiruvananthapuram, which is in the lower quartile, observed a difference of $-0.4 K$. In the upper quartile, Kasaragod and regions of Kannur had positive precipitation differences, and in the lower quartile, Alappuzha and regions of Kottayam and Pathanamthitta. Period 2 humidity witnessed a positive difference in the state's upper tail and all regions in the lower tail, except Idukki. The maximum temperature in the lower tail exhibited positive variations in Ernakulam and Kottayam.

Kasaragod and Kannur, as well as Thiruvananthapuram and Kollam, both experienced values greater than $-0.4 K$ in the upper and lower tails of the mean temperature difference, respectively. The maximum temperature in the upper tail fluctuated positively in Idukki, Alappuzha, Pathanamthitta, Kollam, and Thiruvananthapuram during period 3; similarly, the lower tail showed positive variations in Kasaragod, Thrissur, Palakkad, Ernakulam, Kollam, and Thiruvananthapuram. The regions of Idukki, Pathanamthitta, and Kollam experienced a difference of $-0.15 K$ in the upper quartile of mean temperature.

The southern and northern parts of Kerala's upper and lower tails of humidity, respectively, showed negative variations during Zaid in period 1. The disparities in the lower

quartile were found to be -0.6% across the state in period 3. For both tails, the same pattern was observed for the maximum temperature (-0.4 K) in period 1. Kasaragod and Kannur experienced positive differences in precipitation during period 2; however, during period 3, both districts exhibited negative differences in both quartiles.

3.4.2 Maximum areal difference

The humidity during period 1 in the Ernakulam district exhibited no variations, and the state's maximum temperature ranged from -0.1 to -0.3 K , as shown in Fig. 16.

The average temperature difference in Idukki observed values greater than or equal to -0.35 K . However, Kasaragod and Kannur showed temperature differences that were lower than -0.15 K . In Thrissur, Palakkad, and Idukki districts during period 2, there were positive changes in humidity. Variations in the maximum temperature experienced positive deviations in the districts of Kozhikode, Malappuram, Pathanamthitta, Kollam, Thiruvananthapuram, and some parts of Kannur, Wayanad, Palakkad, and Idukki. Precipitation in the districts of Kasaragod, Kannur, Kozhikode, and Wayanad exhibited positive changes. Maximum temperature differences higher than 0.1 K were observed in the districts of Kozhikode, Wayanad, and Malappuram

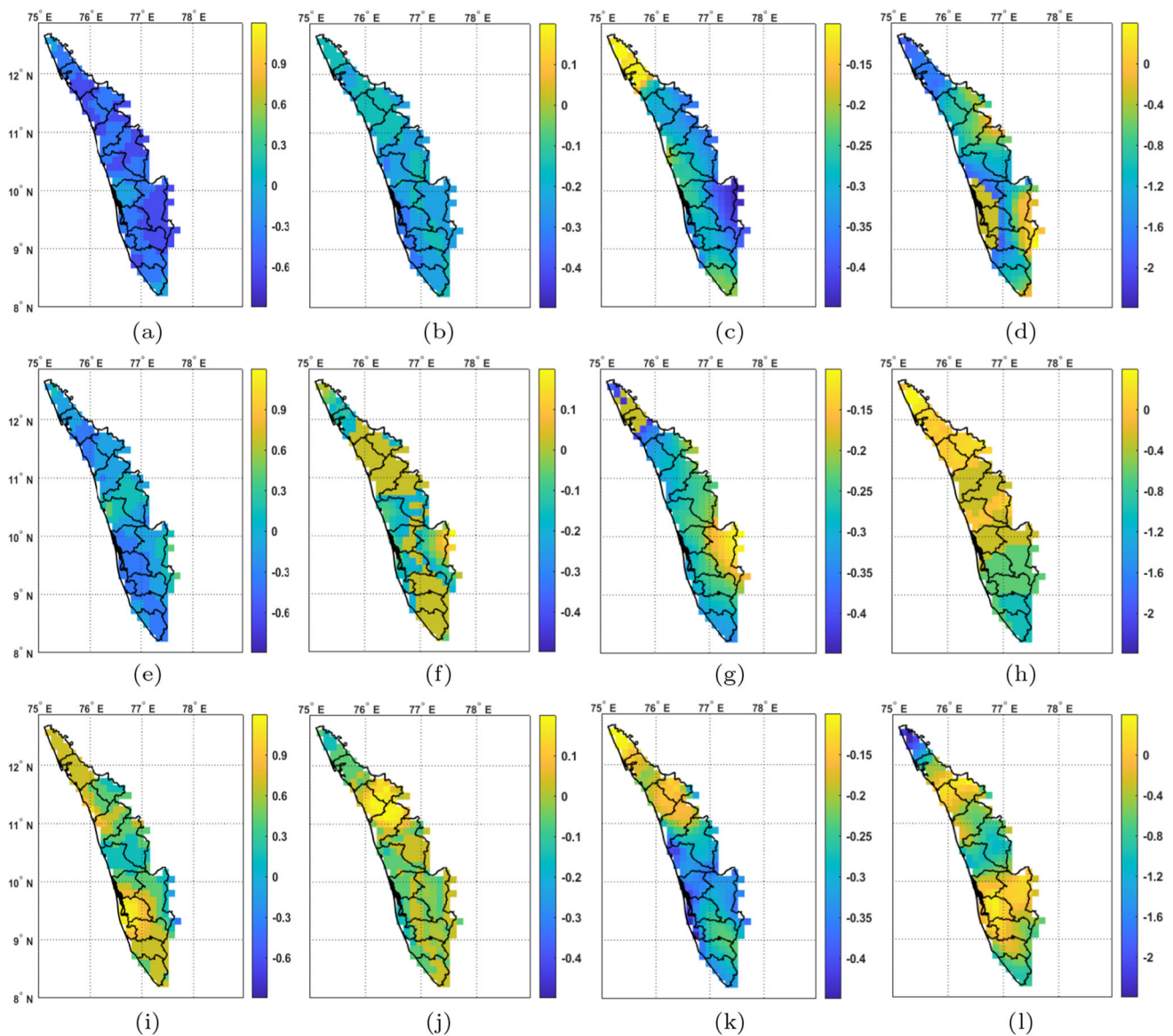


Fig. 16 Annual maximum areal difference: Period 1 (a) relative humidity, (b) maximum temperature, (c) mean temperature, and (d) precipitation; Period 2 (e) relative humidity, (f) maximum temperature, (g)

mean temperature, and (h) precipitation; Period 3 (i) relative humidity, (j) maximum temperature, (k) mean temperature, and (l) precipitation

during period 3. In these areas, the average temperature varied from -0.2 K to -0.15 K . There were noticeable positive fluctuations in the precipitation in several areas of Kannur, Kozhikode, Wayanad, Ernakulam, Kottayam, Idukki, and Pathanamthitta.

Positive changes were observed in the state as a whole in period 3 for relative humidity. However, for maximum temperature in period 1, negative differences were recorded. In several areas of Idukki, precipitation during periods 1 and 3 exhibited no variations.

In the districts of Kasaragod, Kannur, Kozhikode, Palakkad, and some areas of Wayanad, Malappuram, Thrissur, Ernakulam, Kottayam, Pathanamthitta, and Idukki, no variations were recorded during period 1 of Kharif (Fig. 17). Significant variations in the maximum temperature (-0.4 K) were observed in Alappuzha. Mean temperature differences higher than -0.15 K were recorded in the districts of Kozhikode, Wayanad, and Malappuram. During period 2, for humidity, positive differences were observed in Kozhikode, Wayanad, Malappuram, Palakkad, and the regions of Thrissur and Idukki. The districts of Thrissur, Palakkad, Ernakulam, Kottayam, Idukki, Pathanamthitta, Kollam, and some regions of Thiruvananthapuram and Malappuram depicted no difference in maximum temperature. The Idukki district showed the least negative changes in mean temperature. Positive differences in precipitation can be observed in Kasaragod and Kannur. Kasaragod witnessed a difference in the humidity of more than 0.6% during the third period. The Maximum temperature in the districts of Kasaragod and Kannur exhibited difference greater than 0.1 K . In some parts of Wayanad, positive fluctuations in precipitation were observed.

In the districts of Wayanad, Malappuram, Thrissur, Palakkad, and Idukki during Kharif in period 3, difference in humidity values of more than -0.6% were recorded. The state as a whole showed negative disparities in the maximum temperature throughout period one. Compared to periods 2 and 3, the mean temperature in period one exhibited small negative differences. Except for Kozhikode and Wayanad in the third period, precipitation experienced negative shifts throughout the state.

In the Kozhikode and Wayanad regions, the maximum temperature difference during period 1 of Rabi ranged from -0.3 to -0.4 K (figure not shown). The average temperature varied from -0.35 K to -0.4 K in the Kozhikode, Wayanad, and Idukki districts. The least negative difference noticed in precipitation was in the district of Kasaragod. Idukki, Pathanamthitta, and Kollam experienced difference in humidity levels of -0.6% during period 2. Positive differences in maximum temperature were recorded in the districts of Malappuram, Alappuzha, Kottayam, Pathanamthitta, Kollam, and some parts of Kasaragod, Kozhikode, Wayanad, Palakkad, Ernakulam, Idukki, and Thiruvananthapuram. The mean temperature in the Idukki district varied by -0.15

K , and precipitation in regions of Palakkad showed positive differences. During period 3, humidity variations greater than 0.9% were observed in Pathanamthitta. The districts of Kozhikode, Wayanad, and Malappuram depicted maximum temperature variations greater than 0.1 K . Precipitation levels witnessed positive differences in the districts of Alappuzha, Kottayam, Pathanamthitta, and Kollam.

The state's overall humidity difference during Rabi's first period was -0.6% . Compared to periods 2 and 3, all districts experienced negative shifts in the maximum temperature during period 1.

High negative humidity variations (-0.6%) were noted in the districts of Alappuzha, Kottayam, Idukki, Pathanamthitta, Kollam, Thiruvananthapuram, and some areas of Ernakulam during Zaid in period 1 (figure not shown). In the districts of Kasaragod, Kannur, Kozhikode, Wayanad, Malappuram, and Palakkad, positive deviations in maximum temperature were observed. In Idukki, the difference in average temperature was more than -0.4 K . The precipitation exhibited positive differences in Kasaragod and some regions of Kannur. In Kasaragod, Kannur, and some parts of Kozhikode and Wayanad during period 2, humidity showed negative differences. Positive variations in maximum temperatures have been noted in some areas of Wayanad. An average temperature difference of more than -0.15 K was recorded in the Idukki district. The districts of Kasaragod and Kannur exhibited a positive difference in precipitation. In period 3, the districts of Alappuzha, Kottayam, Idukki, Pathanamthitta, and Kollam recorded humidity variations of more than -0.9% . A maximum temperature difference of more than 0.1 K was recorded in Idukki. Precipitation observed positive differences in Kottayam and some areas of Ernakulam, Idukki, and Pathanamthitta.

Period 1 of Zaid witnessed humidity fluctuations in the north that were positive, and in the south that were negative. In periods 2 and 3, positive fluctuations in the southern part were observed. The Northern part recorded positive deviations in the maximum temperature during period 1, while the Southern part witnessed negative deviations. For precipitation, in periods 1 and 2, Kasaragod depicted positive differences.

3.5 Characteristics of the parameters affecting paddy crop

In order to better understand the traits of the variables that affect crops, paddy, a crucial crop grown in Kerala over the three seasons, is taken into account (Department of Agriculture and Welfare (2019)). They are grown in regions having high humidity, reliable water supply, a mean temperature of 21 to 37 degree Celsius, and a maximum temperature ranging between 40 to 42 degree Celsius (Government of India (2015)).

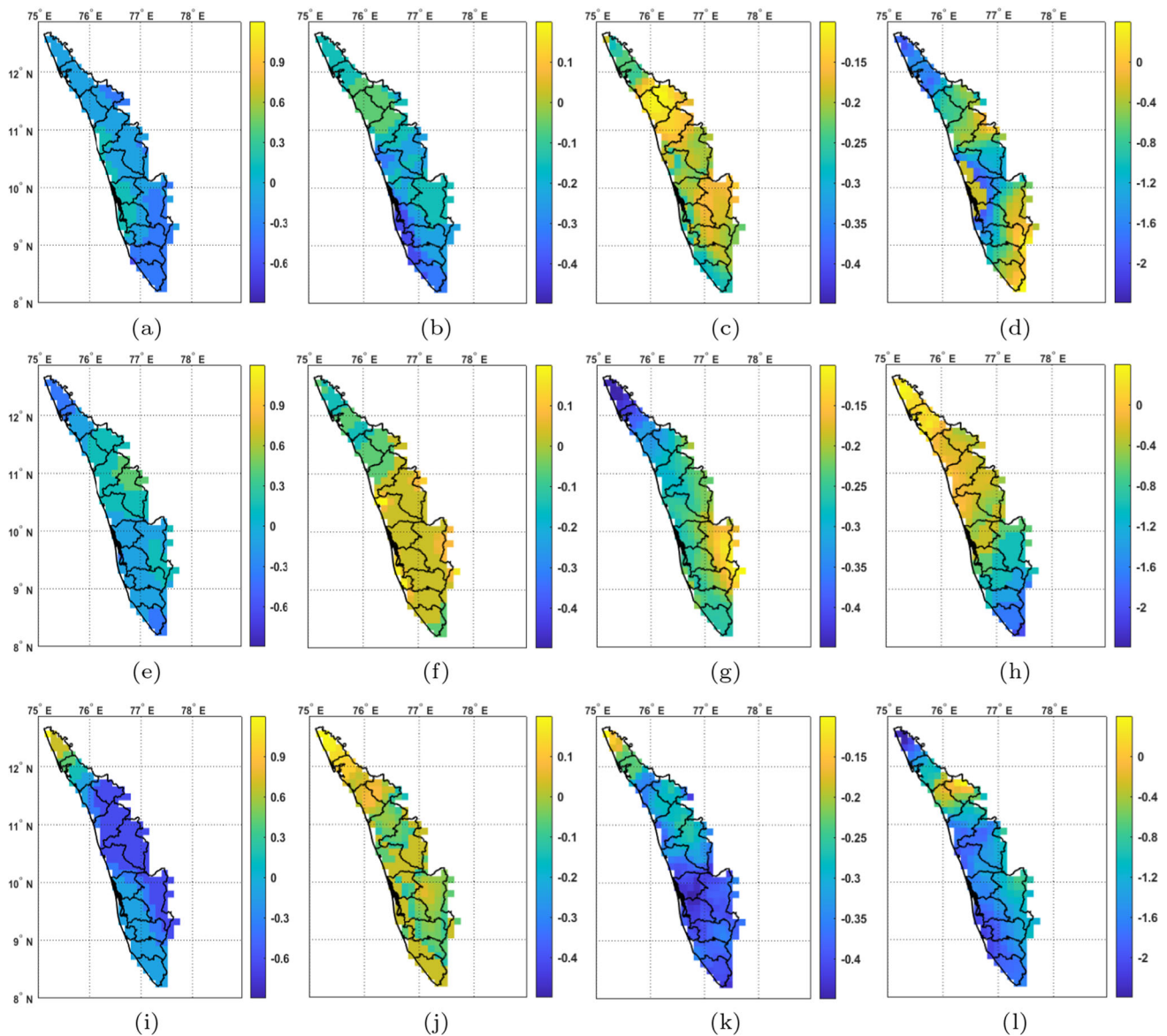


Fig. 17 Seasonal maximum areal difference for Kharif: Period 1 (a) relative humidity, (b) maximum temperature, (c) mean temperature, and (d) precipitation; Period 2 (e) relative humidity, (f) maximum temper-

ature, (g) mean temperature, and (h) precipitation; Period 3 (i) relative humidity, (j) maximum temperature, (k) mean temperature, and (l) precipitation

According to our study, it was seen that Kerala in 2019 witnessed high values of annual mean temperature and precipitation. In the same year, a decrease in the area of paddy by 77.38% was observed (Department of Agriculture and Welfare (2019)). High mean temperatures may have forced farmers to depend on some other crops causing a decline in the paddy area which in turn affects the overall productivity. Based on the study (Giridhar et al. (2022)), the CPLI (Crop Production Loss Index) for paddy in Thiruvananthapuram was found to be 0.020. This could be a consequence of the increase in maximum temperature, humidity, and precipitation that our model PCNT observed. Studies even indicate

that the growth of paddy in Kerala can be impacted by a slight increase in temperature (Nambudiri (2023)). Our proposed model found that the maximum temperature in Kharif during 1987 increased while the humidity and precipitation decreased, resulting in a decline in the area and productivity of the paddy crop, providing another example of how the parameters affect the crops (Government of Kerala (1987)).

In a nutshell, it is found that the trend of the area and the productivity of the paddy showed significant decreasing ($Z = -8.63$) and increasing ($Z = 8.05$) trends, respectively. At the same time, a significant trend is found for the precipitation ($Z = 2.66$), relative humidity ($Z = 0.93$), mean temperature

($Z = 4.03$), and maximum temperature ($Z = 2.14$) using the MK test.

4 Discussions

In this study, a unique probabilistic method called the probabilistic convolution neighbourhood technique (PCNT) for assessing spatio-temporal changes was developed. The developed methodology not only emphasises on spatial and temporal coherence but also carefully monitors variations occurring in areas with high and low values of distribution. This technique was applied to various parameters majorly affecting the crops—namely, relative humidity, maximum temperature, mean temperature, and precipitation. The main advantage of the proposed methodology includes the ability to observe distributional changes at all grid points, and the fact that every point is influenced by its neighbouring points, including the anomalies.

Till date, numerous studies were developed that take account of spatio-temporal changes (Kamruzzaman et al. (2018), Abaje et al. (2018), Rao et al. (2020)), but in all these studies, the spatial and temporal characteristic are analysed separately. Some studies like Mitra and Seshadri (2019), Nanzad et al. (2019), and Wu et al. (2008) wherein only outliers are considered without considering the spatio-temporal relevance.

In general, the proposed methodology PCNT depicts an increase in mean temperature, relative humidity, precipitation, and maximum temperature for annual inter-vicennial variations.

One of the limitations of the present study is finding out the probable distribution of the dataset. The conclusions may vary depending on the choice of distribution.

5 Conclusions

An important global problem is the outgrowth of aberrant climate conditions. Several economic damages have resulted from this, particularly in the agricultural sector. India is one of those nations that is severely impacted by erratic weather patterns. A methodology must be developed in order to analyse these patterns and identify the changes.

The Probabilistic Convolution Neighborhood Technique (PCNT), a novel probabilistic method introduced in this research, is one such approach that identifies the temporal and spatial coherence in each of the location-specific time series, which detects changes in climate variables. This methodology studies the variations in climate variables that affect crops: relative humidity, precipitation, and mean and

maximum temperatures. The IMDAA dataset is used to analyse climate variability because of its high resolution. The study is conducted over the spatial domain of Kerala on a seasonal (Kharif, Rabi, and Zaid) and annual scale.

The proposed method was applied and changes in climatic variables over Kerala were analysed for the time period 1980–2020. The variability of different parameters over Kerala having extreme and moderate values was also scrutinized using PCNT.

The following are the main findings obtained from the study:

1. It is seen that in Kharif and Rabi, seasonal temporal features exhibit a trend in which the variables precipitation and humidity are directly proportional to one another and inversely proportional to temperature;
2. Annual spatial features in the regions of Idukki, Malappuram, Thrissur, and Palakkad displayed similar patterns. These trends were visible in Idukki during the seasons of Rabi and Zaid and also during Kharif in Wayanad and Kannur;
3. The trend of the temporal data was analysed using the Mann-Kendall (MK) test to check whether the increasing or decreasing trend of the variables is statistically significant or not. All parameters show a statistically significant trend (90 %) on an annual (except precipitation) and seasonal scale (except Zaid). The observed significance for humidity, mean temperature, precipitation, and maximum and mean temperatures during Kharif and Rabi, respectively, were greater than 90%. Similar to our study, Roy (2015) has also evaluated that, the relative humidity for Rabi and maximum temperature for Zaid were found to be insignificant;
4. The climate characteristics that are specific to each region can be used to explain the findings on the spatial and temporal pattern. The southernmost and northernmost regions of Kerala, as well as the central region of Kerala, except Ernakulam and Idukki, had comparably low relative humidity according to annual data. Kharif had the lowest temperatures and the highest levels of precipitation and relative humidity when compared to other seasons. In the case of Rabi, low relative humidity and precipitation all over the state except Idukki were observed, whereas the maximum temperature is highest except for Idukki. In Zaid, the northernmost part of Kerala experienced high temperatures together with relatively low humidity and precipitation;
5. In the southern region, the mean temperature and precipitation decreased over time in the tails based on the annual data. The seasonal data revealed that during Kharif, the regions of Kannur with high and low val-

- ues for precipitation and relative humidity increased over time. Kerala experienced an increase in relative humidity in the extremes during Zaid;
6. In regions having normal values for distribution, no differences in relative humidity were found. In most of Kerala, the maximum temperature values exhibited a positive difference, showing that the values have increased over time while the mean temperature values have fallen. Seasonal data showed that a decrease in humidity was observed during Kharif;
 7. For the annual data, period 1991–2000 and 2011–2020 witnessed an increase in humidity but a decrease in mean temperature and precipitation. During period 2001–2010, Kasaragod observed increased precipitation and humidity while the mean temperature decreased in Kharif. In Rabi, Kasaragod experienced increased humidity for all periods. Humidity during 2011–2020 increased in Kozhikode, but temperature and precipitation decreased. During Zaid for the same time period, humidity decreased in Idukki and Pathanamthitta, although the maximum temperature increased. Palakkad and Idukki, for the years 1991–2000, recorded a decrease in precipitation, whereas humidity in these districts increased;
 8. In period 2001–2010, Kasaragod witnessed increased precipitation and maximum temperature in the upper quartile for annual data. In the Pathanamthitta and Kollam districts during Kharif for the years 1991–2000, in the lower quartile, the mean temperature highly decreased, and the humidity extremely increased. During the same time span, humidity and precipitation increased in the upper tail of Rabi in Kasaragod, while maximum temperature highly decreased. In the lower quartile, precipitation increased during period 2001–2010 in Thiruvananthapuram and Kollam districts, although maximum temperatures significantly decreased. During period 2011–2020, humidity and precipitation increased in Idukki for both quartiles. In the upper tail, the districts of Kasaragod and Kannur in Zaid during 1991–2009 observed an increase in humidity and precipitation, whereas maximum temperature decreased. A similar pattern was observed in the districts of Alappuzha, Kottayam, and Pathanamthitta in the lower tail;
 9. For regions having normal values, an increase in humidity and maximum temperature were observed in some parts of Idukki during 2001–2010, and Kozhikode experienced an increase in the maximum temperature and precipitation. In Wayanad, for the period 2011–2020, maximum temperature and precipitation during Kharif increased, whereas humidity decreased. For the same period for Pathanamthitta, during Rabi, maximum temperatures decreased while humidity and precipitation increased. The Kasaragod district witnessed an increase in maximum temperature and precipitation during 1991–2000 for Zaid. Humidity showed a decrease in period 2001–2010, while precipitation in Kasaragod and Kannur increased. In Idukki, 2011–2020 witnessed an increase in maximum temperature and humidity;
 10. The most significant crop in Kerala, paddy, was used to analyse the characteristics of the variables that influence the crop. An increase in precipitation and temperature promotes the growth of paddy and improves productivity for a short time span. But a further increase in these parameters can ruin the panicle and reduce productivity. Varied crops require different climatic circumstances, and these meteorological factors have diverse effects on the crops.
- This study analysed spatio-temporal regional characteristics of different climatic variables on an annual and seasonal time scale. Future research can be conducted to examine the direct effect of these variables on crop growth, on a more finer scale.
- Acknowledgements** Authors gratefully acknowledge NCMRWF, Ministry of Earth Sciences, Government of India, for IMDAA reanalysis. IMDAA reanalysis was produced under the collaboration between UK Met Office, NCMRWF, and IMD with financial support from the Ministry of Earth Sciences, under the National Monsoon Mission programme
- Author Contributions** Both the authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Chalissery Mincy Thomas. The first draft of the manuscript was written by Chalissery Mincy Thomas and Archana Nair commented on previous versions of the manuscript. Archana Nair read and approved the final manuscript
- Data Availability** The datasets generated during and/or analysed during the current study are available in the RDS NCMRWF repository, <https://rds.ncmrwf.gov.in/dashboard/download>, and <https://www.ecostat.kerala.gov.in/>
- Code Availability** Not applicable.
- Declarations**
- Conflict of interest** The authors declare no competing interests.
- Ethics approval** The submitted manuscript is original and has not been submitted or published in any other language or form. The results are not manipulated, and the authors didn't use any fabricated data
- Consent to participate** Not applicable.

Consent for publication Not applicable.

References

- Abaje IB, Achiebo PJ, Matazu MB (2018) Spatio-temporal analysis of rainfall distribution in kaduna state, nigeria. *Ghana J Geogr* 10(1):1–21
- Abhinav M, Lazarus TP, Priyanga V, Kshama, A, et al. (2018) Impact of rainfall on the coconut productivity in kozhikode and malappuram districts of kerala. *Curr Agric Res J* 6(2):183–187. Retrieved from <https://doi.org/10.12944/CARJ.6.2.07>
- Auffhammer M, Ramanathan V, Vincent JR (2012) Climate change, the monsoon, and rice yield in india. *Climatic Change* 111:411–424. Retrieved from <https://doi.org/10.1007/s10584-011-0208-4>
- Ayoade JO (2002) Introduction to agroclimatology. Vintage Publisher, Ibadan
- Brenkert A, Malone E (2003) Vulnerability and resilience of india and indian states to climate change: a first-order approximation. *Joint Global Change Res Institute* 65
- Caloiero T (2014) Analysis of daily rainfall concentration in new zealand. *Natural Hazards* 72(2):389–404. Retrieved from <https://doi.org/10.1007/s11069-013-1015-1>
- Coscarelli R, Caloiero T (2012) Analysis of daily and monthly rainfall concentration in southern italy (calabria region). *J Hydrol* 416:145–156. Retrieved from <https://doi.org/10.1016/j.jhydrol.2011.11.047>
- Daloz AS, Rydsaa JH, Hodnebrog Ø, Sillmann J, van Oort B, Mohr CW, . . . Zhang T (2021) Direct and indirect impacts of climate change on wheat yield in the indo-gangetic plain in india. *J Agric Food Res* 4:100132. Retrieved from <https://doi.org/10.1016/j.jafr.2021.100132>
- Daners D (2019) Introduction to functional analysis. NSW 2006, Australia: School of Mathematics and Statistics, University of Sydney
- Dash S, Nair AA, Kulkarni MA, Mohanty U (2011) Characteristic changes in the long and short spells of different rain intensities in india. *Theoretical Appl Climatol* 105(3):563–570. Retrieved from <https://doi.org/10.1007/s00704-011-0416-x>
- Datta P, Behera B, et al. (2022) Climate change and indian agriculture: a systematic review of farmers' perception, adaptation, and transformation. *Environ Challenges* 100543. Retrieved from <https://doi.org/10.1016/j.envc.2022.100543>
- Department of Agriculture C, Welfare F (2019) At a glance 2019. PDF document
- Dias M, Navaratne C, Weerasinghe K, Hettiarachchi R (2016) Application of dssat crop simulation model to identify the changes of rice growth and yield in nilwala river basin for mid-centuries under changing climatic conditions. *Procedia Food Sci* 6:159–163
- Food and agricultural organisation, annual statistical report (Vol. 56). (2005)
- Giridhar B, Raghavendra K, Singh DR, Kuriachen P (2022) Agricultural vulnerability to climate change: a case study of kerala
- Gocic M, Trajkovic S (2014) Spatio-temporal patterns of precipitation in serbia. *Theoretical Appl Climatol* 117:419–431
- Gohari A, Eslamian S, Abedi-Koupaei J, Bavani AM, Wang D, Madani K (2013) Climate change impacts on crop production in iran's zayandeh-rud river basin. *Sci Total Environ* 442:405–419. Retrieved from <https://doi.org/10.1016/j.scitotenv.2012.10.029>
- Goparaju L, Ahmad F (2019) Analysis of seasonal precipitation, potential evapotranspiration, aridity, future precipitation anomaly and major crops at district level of india. *KN-Journal of Cartography Geographic Inf* 69(2):143–154
- Government of India (2015) Ministry of agriculture and farmers' welfare. Website. Retrieved from <https://www.india.gov.in/website-ministry-agriculture-farmers-welfare> (Last accessed 5 April 2023)
- Government of Kerala (1987) Economic review 1987. PDF document. Retrieved from <https://spb.kerala.gov.in/sites/default/files/inline-files/1987.pdf>
- Güçlü YS (2020) Improved visualization for trend analysis by comparing with classical mann-kendall test and ita. *J Hydrol* 584:124674. Retrieved from <https://doi.org/10.1016/j.jhydrol.2020.124674>
- Hosch WL (2022) Gamma distribution. *Encyclopaedia Britannica, inc.* Retrieved from <https://www.britannica.com/science/gamma-distribution>
- Huang S, Huang Q, Zhang H, Chen Y, Leng G (2016) Spatio-temporal changes in precipitation, temperature and their possibly changing relationship: a case study in the wei river basin, china. *Int J Climatol* 36(3):1160–1169
- INCCA (Indian Network for Climate Change Assessment) (2010) Indian network for climate change assessment, india: Greenhouse gas emissions (2007) INCCA. Ministry of Environment & Forests, India
- IPCC-TGICA A (2007) General guidelines on the use of scenario data for climate impact and adaptation assessment. Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA), Intergovernmental Panel on Climate Change
- Ismaila U, Gana A, Tswana N, Dogara D et al (2010) Cereals production in nigeria: problems, constraints and opportunities for betterment. *African J Agric Res* 5(12):1341–1350
- Jagannathan P, Bhalme H (1973) Changes in the pattern of distribution of southwest monsoon rainfall over india associated with sunspots. *Monthly Weather Rev* 101(9):691–700
- Kamruzzaman M, Rahman AS, Ahmed MS, Kabir ME, Mazumder QH, Rahman MS, Jahan CS (2018) Spatio-temporal analysis of climatic variables in the western part of bangladesh. *Environ Develop Sustainability* 20:89–108
- Kim S, Casper R (2013) Applications of convolution in image processing with matlab. University of Washington, 1–20
- Koutsoyiannis D, Onof C (2001) Rainfall disaggregation using adjusting procedures on a poisson cluster model. *J Hydrol* 246(1–4):109–122
- Krishna Kumar K, Rupa Kumar K, Ashrit R, Deshpande N, Hansen JW (2004) Climate impacts on indian agriculture. *Int J Climatol: A J Royal Meteorological Soc* 24(11):1375–1393
- Lal P, Prakash A, Kumar A, Srivastava PK, Saikia P, Pandey A, . . . Khan M (2020) Evaluating the 2018 extreme flood hazard events in kerala, india. *Remote Sens Lett* 11(5):436–445. Retrieved from <https://doi.org/10.1080/2150704X.2020.1730468>
- Leng G, Huang M (2017) Crop yield response to climate change varies with crop spatial distribution pattern. *Sci Reports* 7(1):1463
- Lobell DB, Burke MB (2010) On the use of statistical models to predict crop yield responses to climate change. *Agric Forest Meteorol* 150(11):1443–1452
- Lobell DB, Field CB (2007) Global scale climate–crop yield relationships and the impacts of recent warming. *Environ Res Lett* 2(1):014002
- Ludwig J (2007) Image convolution. <https://web.pdx.edu/jduh/courses/Archive/geog481w07/Students/LudwigImageConvolution.pdf>. (Accessed on June 11, 2023)
- Mahato A (2014) Climate change and its impact on agriculture. *Int J Sci Res Publications* 4(4):1
- Mathew MM, Sreelash K, Mathew M, Arulbalaji P, Padmalal D (2021) Spatiotemporal variability of rainfall and its effect on hydrological regime in a tropical monsoon-dominated domain of western ghats, india. *J Hydrol: Regional Stud* 36:100861. Retrieved from <https://doi.org/10.1016/j.ejrh.2021.100861>

- Mishra B, Tripathi N (2010) Winter agricultural drought detection using modis imagery: a case study of nepal. Proceeding of the 3rd international conference on git for natural disaster management, chiang mai, thailand (pp. 19–20)
- Mishra S, Mishra D, Santra GH et al (2016) Applications of machine learning techniques in agricultural crop production: a review paper. *Indian J Sci Technol* 9(38):1–14
- Mitra A, Seshadri AK (2019) Detection of spatiotemporally coherent rainfall anomalies using markov random fields. *Comput Geosci* 122:45–53. Retrieved from <https://doi.org/10.1016/j.cageo.2018.10.004>
- Motha RP, Baier W (2005) Impacts of present and future climate change and climate variability on agriculture in the temperate regions: North america. *Climatic Change* 70(1–2):137–164
- Mozny M, Tolasz R, Nekovar J, Sparks T, Trnka M, Zalud Z (2009) The impact of climate change on the yield and quality of saaz hops in the czech republic. *Agric Forest Meteorol* 149(6–7):913–919. Retrieved from <https://doi.org/10.1016/j.agrformet.2009.02.006>
- Mukherjee UK, Bagozzi BE, Chatterjee S (2023) A bayesian framework for studying climate anomalies and social conflicts. *Environmetrics* 34(2):e2778
- Nambudiri, S. (2023, Feb). Mild temp rise unlikely to affect paddy, study kochi news - times of india. *The Times of India*. Retrieved from <https://timesofindia.indiatimes.com/city/kochi/mild-temp-rise-unlikely-to-affect-paddy-study/articleshow/9771391>
- Nanzad L, Zhang J, Tuvdendorj B, Nabil M, Zhang S, Bai Y (2019) Ndvi anomaly for drought monitoring and its correlation with climate factors over mongolia from 2000 to 2016. *J Environ* 164:69–77
- Nath K, Jain R, Marwaha S, Arora A (2020) Identification of optimal crop plan using nature inspired metaheuristic algorithms. *Indian J Agric Sci* 90(8):1587–92. Retrieved from <http://krishi.icar.gov.in/jspui/handle/123456789/47171>
- Nithya N (2013) Kerala's agriculture: performance and challenges. *Int J Phys Soc Sci* 3(11):127
- Özdoğan M (2011) Modeling the impacts of climate change on wheat yields in northwestern turkey. *Agric Ecosyst Environ* 141(1–2):1–12. Retrieved from <https://doi.org/10.1016/j.agee.2011.02.001>
- Pant M, Thangaraj R, Rani D, Abraham A, Srivastava DK (2010) Estimation of optimal crop plan using nature inspired metaheuristics. *World J Model Simulation* 6(2):97–109
- Papalexioiu SM, Koutsoyiannis D (2012) Entropy based derivation of probability distributions: a case study to daily rainfall. *Adv Water Resour* 45:51–57
- Planning Commission, India (2007). Kerala development report. Academic Foundation. (Retrieved 30 May 2015)
- Prävălie R, Piticar A, Roșca, B, Sfîcă, L, Bandoc, G, Tiscovschi, A, Patriche, C. (2019) Spatio-temporal changes of the climatic water balance in romania as a response to precipitation and reference evapotranspiration trends during 1961–2013. *Catena* 172:295–31
- PscAriVukal (2020, May) Crops in kerala. Blog post. Retrieved from <https://www.pscarivukal.com/2020/05/crops-kerala-psc-gk.html>
- Raj B, Singh, O (2012) Study of impacts of global warming on climate change: rise in sea level and disaster frequency. *Global Warming - Impacts and Future Perspectives*
- Rani SI, Arulalan T, George JP, Rajagopal EN, Renshaw R, Maycock A, . . . Rajeevan M (2021, Jun) Imdaa: High-resolution satellite-era reanalysis for the indian monsoon region. *Am Meteorolog Soc*. Retrieved from <https://journals.ametsoc.org/view/journals/clim/34/12/JCLI-D-20-0412.1.xml>
- Rao CR, Raju B, Rao AS, Rao K, Rao V, Ramachandran K, . . . others (2016) A district level assessment of vulnerability of indian agriculture to climate change. *Curr Sci* 1939–1946
- Rao CS, Gopinath K, Prasad J, Singh A, et al. (2016) Climate resilient villages for sustainable food security in tropical india: concept, process, technologies, institutions, and impacts. *Adv Agronomy* 140:101–214. Retrieved from <https://doi.org/10.1016/bs.agron.2016.06.003>
- Rao G, Kesava Rao A, Krishnakumar K, Gopakumar C (2009) Impact of climate change on food and plantation crops in the humid tropics of india. *ISPRS Archives* 38(8):W3
- Rao GV, Reddy KV, Srinivasan R, Sridhar V, Umamahesh N, Pratap D (2020) Spatio-temporal analysis of rainfall extremes in the flood prone nagavali and vamsadhara basins in eastern india. *Weather Climate Extremes* 29:100265
- Ray DK, Gerber JS, MacDonald GK, West PC (2015) Climate variation explains a third of global crop yield variability. *Nature Commun* 6(1):1–9
- Rial-Lovera K, Davies WP, Cannon ND (2017) Implications of climate change predictions for uk cropping and prospects for possible mitigation: a review of challenges and potential responses. *J Sci Food Agric* 97(1):17–32. Retrieved from <https://doi.org/10.1002/jsfa.7767>
- Roudier P, Sultan B, Quirion P, Berg A (2011) The impact of future climate change on west african crop yields: what does the recent literature say? *Global Environ Change* 21(3):1073–1083. Retrieved from <https://doi.org/10.1016/j.gloenvcha.2011.04.007>
- Roy AD (2015) Trend detection in temperature and rainfall over rajasthan during the last century. *Asian J Res Soc Sci Human* 5(2):12–26
- Sameer (2021, Jan) Image convolution from scratch. *Analytics Vidhya*. Retrieved from <https://medium.com/analytics-vidhya/image-convolution-from-scratch-d99bf639c32a>
- Saranya S, Amudha T (2016) Crop planning optimization research—a detailed investigation. 2016 iee international conference on advances in computer applications (icaca) (pp. 202–208). <https://doi.org/10.1109/ICACA.2016.7887951>
- Sethi A, Lin C-Y, Madhavan I, Davis M, Alexander P, Eddleston M, Chang S-S (2022) Impact of regional bans of highly hazardous pesticides on agricultural yields: the case of kerala. *Agric Food Security* 11(1):1–13
- Sivajothi R, Karthikeyan K (2016) Analysis of monthly rainfall data prediction for change of economic environment in pampadumpara using gamma distribution. *Res J Pharm Technol* 9(9):1477–1482
- Sneha H (2018, November 30) 2d convolution in image processing. *All About Circuits*. Retrieved from <https://www.allaboutcircuits.com/technical-articles/two-dimensional-convolution-in-image-processing/>
- Song X, Zou X, Zhang C, Zhang J, Kong F (2019) Multiscale spatio-temporal changes of precipitation extremes in beijing-tianjin-hebei region, china during 1958–2017. *Atmosphere* 10(8):462
- Sudha T (2011) Opportunities in participatory planning to evolve a land use policy for western ghats region in kerala. Department of Town and Country Planning, Government of Kerala
- Toros H (2012) Spatio-temporal precipitation change assessments over turkey. *Int J Climatol* 32(9):1310–1325
- Varughese AR (2022, Apr) Agrarian distress in kuttanad a wake-up call for urgent climate adaptation. Retrieved from <https://science.thewire.in/environment/kuttanad-agrarian-distress-climate-adaptation-urgent/>
- White JW, Hoogenboom G, Kimball BA, Wall GW (2011) Methodologies for simulating impacts of climate change on crop production. *Field Crops Res* 124(3):357–368
- Wu Z, Schneider EK, Kirtman BP, Sarachik ES, Huang NE, Tucker CJ (2008) The modulated annual cycle: an alternative reference frame for climate anomalies. *Climate Dynamics* 31:823–841
- You L, Rosegrant MW, Wood S, Sun D (2009) Impact of growing season temperature on wheat productivity in china. *Agric Forest Meteorol* 149(6–7):1009–1014. Retrieved from <https://doi.org/10.1016/j.agrformet.2008.12.004>
- Zhang Q, Xu C-Y, Zhang Z, Chen YD, Liu C-I, Lin H (2008) Spatial and temporal variability of precipitation maxima during 1960–2005 in

the yangtze river basin and possible association with large-scale circulation. *J Hydrol* 353(3-4):215–227. Retrieved from <https://doi.org/10.1016/j.jhydrol.2007.11.023>

Zhao J, Guo J, Mu J (2015) Exploring the relationships between climatic variables and climate-induced yield of spring maize in northeast china. *Agricul Ecosyst Environ* 207:79–90

Zhao N, Yue T, Li H, Zhang L, Yin X, Liu Y (2018) Spatio-temporal changes in precipitation over beijing-tianjin-hebei region, china. *Atmospheric Res* 202:156–168

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