Cultivating Climate Comprehension

Analysing Critical Climate-Stress Moments in Semi-Arid Karnataka, India

Final report

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Cover photo by Nabina Chakraborty. Source: Aryan et al. (2025).

TABLE OF CONTENTS

EXECUTIVE SUMMARY

A team of five Wageningen University & Research students specialised in environmental and climate studies conducted a project related to climate change mitigation and adaptation strategies. This project is commissioned by WELL Labs and concerns the analysis of critical climate-stress moments in Karnataka, India. Climate change projections are often not useful for agricultural purposes because these are not region specific enough and they use the yearly timescale and do not include smaller timescales such as the seasonal or daily time scale. Therefore, this poses a challenge for farmers, since farmers are very dependent on understanding the climate to make adequate adaptation decisions.

Our project focused on two regions in the state of Karnataka in India, namely Raichur and Chikkaballapur. In these regions, local farmers and communities are facing an increasing amount of critical climate-stress moments. Critical climate-stress moments are explained as “those moments when households, communities, and the livelihood systems they depend on, are especially vulnerable to climate and weather-related risks and hazards”. Since the increasing frequency of critical climate-stress moments in these regions, access to information is key to make sure to adapt to the threatening climate. Next to this, current models and future-scenario analysis have proven to not be helpful for regional data analysis due to the high spatial variability of the data, which is insufficiently represented in these models. The hydrological model that is being developed by WELL Labs as a part of the larger CLARITY project currently misses the region-specific knowledge regarding changes in critical climate-stress moments

The aim of the project is to identify and analyse critical climate-stress moments in the districts of Raichur and Chikkaballapur in Karnataka. The research question states:

What historical trends, regarding critical climate-stress moments in agriculture, can be observed in Raichur and Chikkaballapur, India, based on:

- *temperature data between 1951 and 2024?*
- *rainfall data between 1901 and 2024?*

Next to this, comparisons between rainfall datasets were made to check how well they compared. One of the comparisons was made between modelled IPED dataset (0.1° resolution) and the IMD dataset (0.25° resolution) is performed, the other comparison was done between observational rainfall data of several stations in Raichur and the IMD rainfall data of the same region. All analyses done in the project used Python to make several graphs on variables related to temperature and rainfall.

A comparison of IMD and IPED rainfall data for Raichur and Chikkaballapur shows stronger correlation during the Kharif season (high-rainfall period) compared to Rabi season (low-rainfall period). In Raichur, the annual variability between the two datasets in appears similar based on the median value. However, IPED data shows slightly wider range of rainfall than the IMD data. While in Chikkaballapur, the median of IPED data slightly higher than IMD rainfall. For the comparison of IMD and observation rainfall data in Raichur, the IMD data show higher median values and higher range of rainfall indicating a tendency to overestimate rainfall.

The main limitations of the research for this report are that the timespan chosen as the representative climate period for the temperature data covers 20 years rather than the standard 30-year period in climate sciences. This does come with its limitations but due to the size of the dataset (70 years) it was decided upon those 20 years covers most natural variability in the climate system and yet allows enough time between the time periods to be able to compare them. Additionally, the critical climate stress moments thresholds were designed for agriculture in different regions of India than the ones

analysed in this research. Therefore not every critical threshold was applicable to the study regions. Temperatures in Chikkaballapur do not exceed the critical threshold of 40°C, instead the threshold was based on the corresponding percentile in Raichur for 40°C. This does mean that any changes in the hot streaks in Chikkaballapur concern very hot days for this region but not the critical threshold for agricultural practices.

In conclusion, results indicate that the trend for days above 40°C has been increasing for Raichur, with a rate of 19 extra hot days per year, every 100 years. Winter temperatures show to be increasing with 0.6°C and 0.9°C in Raichur and Chikkaballapur respectively. For both regions, the onset of the Kharif season starts earlier in the year, with a rate of 6 days every 100 years. The amount of days with heavy rainfall is increasing in Raichur with an extra 2 days of heavy rain per year, every 100 years. Rainfall intensity increases with a rate of 3 and 1 mm of extra rainfall per rainy day every 100 years. No change was found for the number and length of dry spells, the amount of rainfall in September and October and the number of drought years.

Based on our conclusions and the discussion with local stakeholders we recommend doing more crop specific research in addition to the general climate trends. Furthermore, additional datasets have been mentioned to be available, which we think is valuable to use if this means higher spatial and temporal resolution. This could lead to further insights on heavy hourly rainfall, which was not yet possible in this analysis. Even though we recommend more specific research, we advise to be careful when looking into only the most recent data to make sure that the internal climate variability is taken into account. Moreover, we recommend to investigate how crops react to multiple climate stresses at the same time combined with looking into neighbouring districts before using this information to guide decisions in other areas. Next to the climate effects on crop and livestock, it is important to keep health impacts of the workers in mind, especially when looking extreme temperatures. Lastly, we consider stakeholder involvement throughout the process to be a vital part of reaching the goal of helping local farmers, and we advise to continue with this during further research.

1. INTRODUCTION

1.1 BACKGROUND INFORMATION

As part of the academic consultancy training course, a team of five Wageningen University & Research students specialised in environmental and climate studies conducted a project related to climate change mitigation and adaptation strategies. This project is commissioned by WELL Labs and concerns the analysis of critical climate-stress moments in Karnataka, India. Semi-arid regions in Karnataka state are facing intensifying climate-stress, impacting many smallholder farmers who depend on agriculture for their livelihoods (Srinidhi & WUR , 2025). Extreme weather events, shifting monsoon patterns, and an increasing frequency of extreme temperatures threaten economic stability (Srinidhi & WUR , 2025). Therefore, access to information is essential for local farmers and communities to enhance the adaptive capacity of the regions. In short, this project will identify and analyse critical climate-stress moments in the districts of Raichur and Chikkaballapur in Karnataka.

1.1.1 WELL Labs

This project is commissioned by WELL (Water, Environment, Land and Livelihoods) Labs. WELL Labs is an Indian research centre based at the Institute for Financial Management and Research (IFMR) Society. The organisation co-creates research and innovation projects for social impact in the areas of land and water sustainability (WELL Labs, n.d.). The insights gained from the data analysis may be valuable for the overarching CLARITY (CLimate Adaptation and Resilience In Tropical drYlands) project as an indication for potential adaptation pathways. This CLARITY project addresses the critical need to identify equitable, sustainable and climate-resilient development pathways in tropical drylands (Majumdar, 2025).

1.1.2 Study regions

The study regions investigated in this project are the semi-arid regions of Raichur and Chikkaballapur in the state of Karnataka, India. The location of the regions is shown in Figure 1. Karnataka is one of the largest rainfed agricultural areas of India, where food production is very dependent on the monsoon season (Rajegowda et al., 2009). Within the state, the weather varies a lot on a spatial and temporal scale. More general climate conditions vary from (semi-)arid in the plateau region, which covers most of Karnataka, to (sub-) humid or tropical in the Western Ghats (mountain range) and at the coast (Sridhara et al., 2020). Although Karnataka is one of the most vulnerable states in terms of droughts (Kumar et al., 2016), an annual increasing trend in rainfall has been observed over the past 37 years (Sridhara et al., 2020). Overall, more variation in precipitation was observed during the months leading up to the monsoon. For agriculture, this time of the year is important for land preparation. Besides rainfall, the observed temperature changes can lead to reductions in crop yield (Sridhara et al., 2020). For the farmers the Kharif (monsoon) season falls between the months June and October and the Rabi (winter) season falls between the months November until April and these are the most important seasons for agricultural activities (Srinidhi et al., 2024).

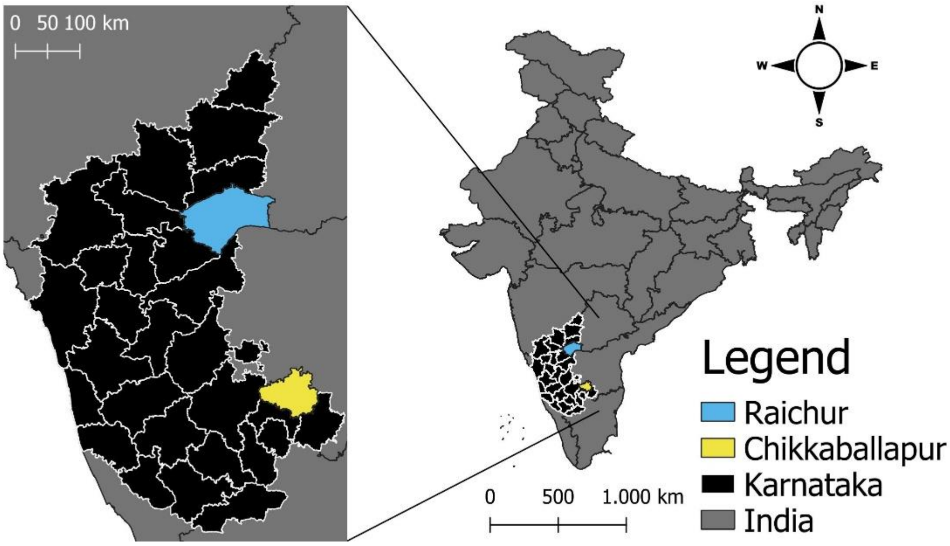


Figure 1. Study regions in Karnataka, India. Shapefile sources: Tiwari (2020) and Geographical Analysis (2023).

Raichur region has a net sown area of 4,750 km^2, and 70% of its population depends on agricultural activities (Aryan et al., 2025). The region is surrounded by two large rivers, the Krishna and the Tungabhadra. Around one third of the agricultural area is irrigated and is dependent on the canals within the region. However, the water availability of the canals is not equally distributed and poses a problem for distant farms (Aryan et al., 2025).

Chikkaballapur region has an area of 4,045 km^2, and 65% of its population depends on agricultural activities (Sundaresan et al., 2025). Agriculture and drinking water supply is dependent on groundwater, since there are no perennial streams in this region. However, the groundwater aquifers have been depleted for almost two decades (Sundaresan et al., 2025). Crops grown in this region are ragi, maize, vegetables, fruit crops, pulses together with oil seeds, as well as horticulture (NABARD, 2023).

1.2 PROBLEM DESCRIPTION

Climate change projections have shown the expected average trends in precipitation and temperature for the next decades. However, oftentimes these projections are unfit to use for agricultural purposes (Srinidhi et al., 2024). This poses a challenge as farmers are very dependent on understanding climate risks on a seasonal, monthly or even daily time scale in order to make adequate adaptation decisions (Srinidhi et al., 2024). The climate risks at such moments are referred to as critical climate-stress moments. These are defined by Groot et al. (2017, p. 10) as “those moments when households, communities, and the livelihood systems they depend on, are especially vulnerable to climate and weather-related risks and hazards”. Since local farmers and communities in semi-arid regions are facing an increasing frequency of critical climate-stress moments, access to information is key to enhance their adaptive capacity (Srinidhi et al., 2024). Next to this, current models and future-scenario analysis have proven unfruitful for regional data analysis due to the high spatial variability, which is insufficiently represented in these models (Srinidhi & WUR, 2025). The hydrological model that is being developed by WELL Labs as a part of the CLARITY project currently lacks the region-specific data-driven knowledge regarding changes in critical climate-stress moments.

1.3 RESEARCH QUESTION AND AIM OF PROJECT

This project primarily aimed to close the existing knowledge gap by providing WELL Labs with historical data analyses of temperature and rainfall to indicate changes in critical climate-stress moments in Raichur and Chikkaballapur. This has been done in an agricultural context. The findings may be used to develop adaptation and mitigation strategies for the local farmers and communities, while also contributing to the broader goals of the CLARITY project. Additionally, the results are communicated through a blog post on the WELL Labs website and a supporting infographic to enhance the understanding among the directly affected communities.

The research question states:

What historical trends, regarding critical climate-stress moments in agriculture, can be observed in Raichur and Chikkaballapur, India, based on:

- *temperature data between 1951 and 2024?*
- *rainfall data between 1901 and 2024?*

The critical climate-stress moments we have considered are listed in Table 1 in section 1.4.

Next to this, a comparative analysis is conducted between modelled rainfall data with spatial resolutions of 0.1° and 0.25°, as well as a comparative analysis between observational rainfall data of several stations in Raichur and modelled IMD rainfall data of 0.25° in Raichur.

1.4 CRITICAL CLIMATE STRESS MOMENTS

The critical climate-stress moments discussed in this report are summarised in Table 1. The impact of concern explains why it is a critical climate-stress moment for agriculture. The information in the last column corresponds to the relating chapter in this report.

Table 1. Critical climate-stress moments and their impacts of concern discussed in this report.

Climate stress	Impact of concern	Corresponding chapter in this report
Rising summer temperatures, more days above 40°C	This leads to heat stress in livestock. Yields of crops ready for harvest are reduced.	3.1.1 Days with temperatures above a critical threshold
Unreliable winter conditions	Warmer winter temperatures have reduced yield as an effect.	3.1.2 Temperatures during Rabi season
Delayed rainfall at the start of the Kharif season	Losses due to a shorter growing season in the Kharif season	3.2.1 Onset Kharif
Days with heavy rainfall in a single day	Losses at time of harvest, during sowing time or during nursery development stages	3.2.2 Heavy rainfall 3.2.5 Rainfall intensity
Dry spells in July and August (after monsoon onset)	Dry spells lead to heat stress and higher risks of disease in livestock, especially with no rainfall for 20-25 days.	3.2.3 Dry spells
High rainfall in September and October	Damaging Kharif crops, delaying the sowing of Rabi crops which cause them to be exposed to a hotter period of the summer	3.2.4 Rainfall September and October

Frequency of drought years	Decreasing ground water buffers, causing meteorological droughts to be more and more correlated with hydrological droughts.	3.2.6 Drought years

1.5 READING GUIDE

The next chapter, Chapter 2, focuses on the methodology of the project including the sources of the temperature and rainfall data. Chapter 3 provides the results of the temperature and rainfall data analysis for both the Raichur and Chikkaballapur region. Chapter 4 provides the results of two comparative analyses; the first section discusses the results of the comparison between modelled rainfall data of 0.1° and 0.25° spatial resolutions. The second section discusses the comparison between the observed rainfall data of several stations in Raichur and the modelled IMD rainfall data of 0.25 degree of Raichur. Chapter 5 discusses interpretations, implications and limitations of the project, whereas Chapter 6 concludes the main findings of the project. Lastly, Chapter 7 outlines our recommendations resulting from this project. Besides the predetermined critical climate-stress moments, additional analysis of temperature and rainfall data has been performed. The methodology and results of the additional temperature data analysis can be found in Appendix A and of the additional rainfall data analysis in Appendix B.

2. METHODOLOGY

2.1 DATA SOURCES AND PRE-PROCESSING

For both study regions Raichur and Chikkaballapur, a data analysis is conducted to identify trends in variables linked to critical climate-stress moments related to temperature and rainfall. Therefore, the three climate variables that are investigated included minimum and maximum temperature data, and rainfall data, as shown in Table 2. A summary of the data including their sources, units, temporal and spatial resolutions, type, and period is provided in Table 2.

Table 2. Summary of data sources, resolutions, and periods for temperature and rainfall data. ** The available years differ between the observational data points.*

	Minimum temperature	Maximum temperature	Rainfall		
Source	IMD High resolution (Srivastava et al. A. K., 2009)	IMD High resolution (Srivastava et al. A. K., 2009)	IMD New High Spatial Resolution data (Pai et al., 2014)	Indian Precipitation Ensemble Dataset (IPED) (Peringiyil et al., 2025)	Provided by WELL Labs
Temporal resolution	Daily	Daily	Daily	Daily	Daily
Spatial resolution	1°	1°	0.25°	0.1°	-
Type	Gridded	Gridded	Gridded	Gridded	Observational
Period	1951-2024	1951-2024	1901-2024	1991-2023	2000-2023*
Unit	°C	°C	mm	mm	mm

The IMD datasets are based on reanalysis data, meaning that this is model output adjusted to observation data. Datasets have been clipped to the respective regions with the use of shapefiles (WELL Labs & Saksham, 2025b; WELL Labs & Saksham, 2025c), whereafter the datapoints in the regions were used for the main climate trend analysis.

Comparative analysis has been carried out on the rainfall data. The first comparison involved gridded rainfall data with spatial resolutions of 0.1° and 0.25° for both Raichur and Chikkaballapur. The second comparison focused on Raichur, where the 0.25° resolution rainfall data was compared against the observational rainfall data including several measurements of regional rain gauge stations (WELL Labs & Saksham, 2025a).

2.2 DATA ANALYSIS

Three climate variables were used for the data analysis: minimum temperature, maximum temperature and rainfall. The analysis is done for both study regions (Raichur and Chikkaballapur). The analysis was conducted using Python and was carried out with reproducibility in mind. The data scripts have been made available through our projects' GitHub repository (link to GitHub).

2.2.1 Temperature data analysis

The temperature analysis was based on two temperature variables: minimum daily temperature (Tmin) and maximum daily temperature (Tmax). Using these variables, two derived metrics were calculated:

- Mean daily temperature (Tavg):

$$Tavg = \frac{Tmax + Tmin}{2} \quad (1)$$

- Diurnal Temperature Variation (DTV):

$$DTV = Tmax - Tmin \quad (2)$$

Tavg serves as a proxy for the mean daily temperature (°C), though this is a simplification and may not fully capture the true average over a 24-hour period.

For most of the analysed variables related to temperature, trends were made based on the full data period (1951-2024). Next to this, comparisons has been made between the climate of the recent two decades (2005-2024) and the first two decades (1951-1970) in the dataset. This concept is referred to as representative climate periods to establish long-term statistical significance for a selected variable. While it is standard practise in climate science to use a 30-year period to define a representative climate, available temperature (both Tmin and Tmax) datasets span about 70 years. A 30-year representative climate period would cover almost half of the datasets, potentially limiting the analysis. To preserve analytical flexibility, a shorter 20-year period was chosen, similarly done in a case study by Giorgi and Bi (2005). This decision is not expected to influence the quality of the results, as we expect a 20-year period to be sufficient to capture natural climate variability and serve as a base to assess long-term temperature trends. Also, the Rabi (winter) season and Kharif (monsoon) season to investigate seasonal trends. We used the months November until April for the Rabi season and the months June until October for the Kharif season (Srinidhi et al., 2024).

The analysed temperature variables were hot days, hot streaks and temperatures in the Rabi season. The thresholds taken for these variables are based on the paper of Srinidhi et al., (2024). A hot day is defined as a day exceeding the critical threshold of 40°C. As no days with recorded temperatures above the 40°C threshold occurred in the dataset of Chikkaballapur, an alternative threshold was developed to enable a comparative analysis for the occurrence of hot days over the years in both regions. In Raichur, days above 40°C corresponded to the 96.5th percentile (i.e., 3.5% of the hottest days) of maximum daily temperatures (Tmax) between 1951-1970. Applying the same percentile to Tmax data for Chikkaballapur resulted in a temperature of 35°C. Thus, 35°C was selected as the equivalent threshold for defining hot days in Chikkaballapur. Next to this, the temperature analysis includes the concepts of hot streaks. A hot streak is defined as two or more consecutive days with temperatures exceeding the hot day threshold. For hot streaks, the analysis focused on three key indicators for each year: the number of hot streaks, the maximum streak length, and the average streak length. The first and last day a hot day occurred were also investigated. Lastly, a comparison was made between the representative climate periods for Rabi (winter) temperatures. Several statistical tests were used for the analysed temperature variables and the tests used and an explanation for these tests are given in section 2.2.5. For more details on how the temperature data analysis was executed and how the figures were made, see the data scripts stored in our repository.

2.2.2 Rainfall data analysis

The rainfall analysis was based on the rainfall data and is available from 1901-2024. Since we had multiple data points for each region (six for Raichur and five for Chikkaballapur), for all analysed variables related to rainfall, the dataset was averaged over all data years and all data points. For most of the analysed variables related to rainfall, trends were made based on the full data period (1901-2024). Next to this, comparisons has been made between the climate of the recent three decades (1995-2024) and the first three decades (1901-1930) in the dataset. This concept is referred to as representative climate periods to establish long-term statistical significance for a selected variable. A 30-year period was used as it is standard practise in climate science to use this to define a representative climate since the period is long enough to be sufficient to capture natural climate variability. Also, the Rabi (winter) season and Kharif (monsoon) season to investigate seasonal trends. We used the months November until April for the Rabi season and the months June until October for the Kharif season (Srinidhi et al., 2024).

The analysed rainfall variables were onset of the Kharif season, heavy rainfall, dry spells, rainfall in September and October, rainfall intensity, and drought years. The thresholds taken for these variables are based on the paper of Srinidhi et al., (2024). For the onset of the Kharif season, firstly the dataset has been filtered to contain the months 6-10 (June-October). Afterwards the average of all the stations per region have been calculated. Then separately the accumulated rainfall is added, the first time each year that this accumulated value went above 70 mm has been counted as the effective onset for the Kharif season. For heavy rainfall, the number of heavy rainfall days were based on a threshold of 25 mm per day. Dry spells are defined as at least 20 consecutive days of less than 2.5 mm of rainfall per day. For the rainfall of September and October the rain development is analysed referring to the end of the monsoon (in the months of September and October), the amount of rainfall for these months is summed per month per year and compared between years to detect possible changes. For rainfall intensity, the analysis is based on the threshold of 2.5 mm of rainfall per day only including rainy days. A drought year is defined as a year with less than 75% of the average yearly rainfall. For the drought years, there is looked at the frequency over the years.

Several statistical tests were used for the analysed rainfall variables and the tests used and an explanation for these tests are given in section 2.2.5. For more details on how the rainfall data analysis was executed and how the figures were made, see the data scripts stored in our repository.

2.2.3 Additional temperature and rainfall data analyses

The focus of this project was on the critical climate-stress moments. However, additional data analyses have been conducted to create some general trends of temperature and rainfall and to look at other interesting aspects within these datasets with potential consequences to agriculture. As a supplement to the main text, the methodology and results of the additional temperature data analysis is described in Appendix A. This includes the variables number of hot days for Chikkaballapur, general temperature trends (yearly), moving decadal rate of warming, temperature anomalies and climate variability, seasonal (Kharif and Rabi season) temperature change, number of cold days in a year, and consecutive cold days. The methodology and results of the additional rainfall data analysis is described in Appendix B. This includes the variables of total rainfall, number of rainy days, and dry spells.

2.2.4 Comparative Analyses

Comparative analysis was carried out using multiple rainfall datasets. This included gridded rainfall datasets such as Indian Precipitation Ensemble Dataset (IPED) at 0.1° resolution and Indian Meteorological Department (IMD) at 0.25° resolution, along with ground-based observations specifically for Raichur and Chikkaballapur regions. The goals were to understand how each dataset captures the spread of annual rainfall variability in both regions.

2.2.4.1 *Comparison of IMD and IPED of rainfall dataset in Raichur and Chikkaballapur*

Daily rainfall from IPED with 0.1° resolution and the IMD with 0.25° resolution were processed for the comparative analysis over the Raichur and Chikkaballapur for the period 1991-2023. The data was first filtered to ensure the same time frame for all datapoints and subsequently, IMD data was subset to only include grid points that matched IPED coordinates. The datasets were then merged based on these matched coordinates and used to generate the scatter plot by comparing the yearly average of total rainfall across matched coordinates in each region. Additionally, Rabi and Kharif seasons were further analysed.

2.2.4.2 *Comparison of IMD and observational rainfall data in Raichur*

The comparative analysis between observed and IMD rainfall data in the Raichur region was conducted by matching daily rainfall data from multiple ground observation stations to the nearest grid point of the IMD dataset (0.25° resolution) (Figure D1). This analysis was visualised using box plots by calculating the total annual rainfall for each station from both datasets. To ensure consistency in the comparison, only the overlapping period from 2000-2016 was used, as data availability varied over stations. Each station-year pair was matched between the observed and gridded datasets. In parallel, a seasonal statistical evaluation was conducted using the entire available data for each station. Rainfall data were grouped into two agriculturally relevant seasons: Rabi and Kharif.

2.2.5 Statistical analysis

To assess the significance of observed climate trends, various statistical analyses were conducted for the temperature, rainfall and comparative analyses. These methods help determine whether changes over time are meaningful or could have occurred by chance. The threshold to determine a meaningful change was set to $p < 0.05$. If the p-value exceeded 0.05, the exact value will be presented. If the p-value is smaller than 0.05, the value will be presented as $p < 0.05$. If the p-value smaller than 0.01, it will be referred to as $p << 0.05$.

The used statistical methods include:

- **Linear regression**: Applied to identify and quantify trends over time, showing whether variables such as temperature or rainfall are increasing or decreasing significantly.
- **Linear regression with interaction terms**: Used to test whether different variables (e.g., maximum vs. minimum temperature, or hot days) are changing at significantly different rates over time.
- **Independent t-test**: Conducted to compare group means for metrics like the absolute number of hot days, helping determine if differences are statistically significant between periods.
- **Two-sample t-test**: Used to compare the means of two time periods (e.g., first and last 30 years) to assess whether observed changes in variables like dry spell lengths are statistically significant.
- **Binomial test**: Employed to evaluate whether the frequency of specific events (e.g., dry spells or droughts) in one period significantly deviates from a baseline frequency established in an earlier period.

For the comparative analysis, we used several statistics: Pearson correlation coefficient (r) to measure the strength of the relationship between two datasets, the root mean square error (RMSE) quantifies the average magnitude of error between the datasets, the percentage of RMSE and the p-value of the linear regression assess the statistical significance based on two matched coordinate points in each region.

3. RESULTS

3.1 TEMPERATURE

In this subchapter the results of the temperature critical climate-stress analysis will be discussed. This subchapter is divided in sections on the number of hot days, hot streaks and temperatures during Rabi season. The end of this subchapter includes the main findings related to the temperature data analysis.

3.1.1 Days with temperatures above a critical threshold

3.1.1.1 *Number of hot days*

Hot days are defined as days when the maximum temperature exceeds a specific threshold (40°C for Raichur and 35°C for Chikkaballapur). Although the year-to-year variability is high, with a standard deviation of approximately 12 days in Raichur and 16 days in Chikkaballapur, a clear long-term trend of an increase in the number of hot days is evident in both regions.

Trend analysis shows a significant increase of the number of hot days in both locations ($p << 0.05$), with Raichur (+0.19 days/year) showing a slower rate of change than Chikkaballapur (+0.38 days/year). For the change of number of hot days in Raichur see Figure 2. The graph for Chikkaballapur is located in Appendix A as the critical threshold used is lower than the critical climate stress value.

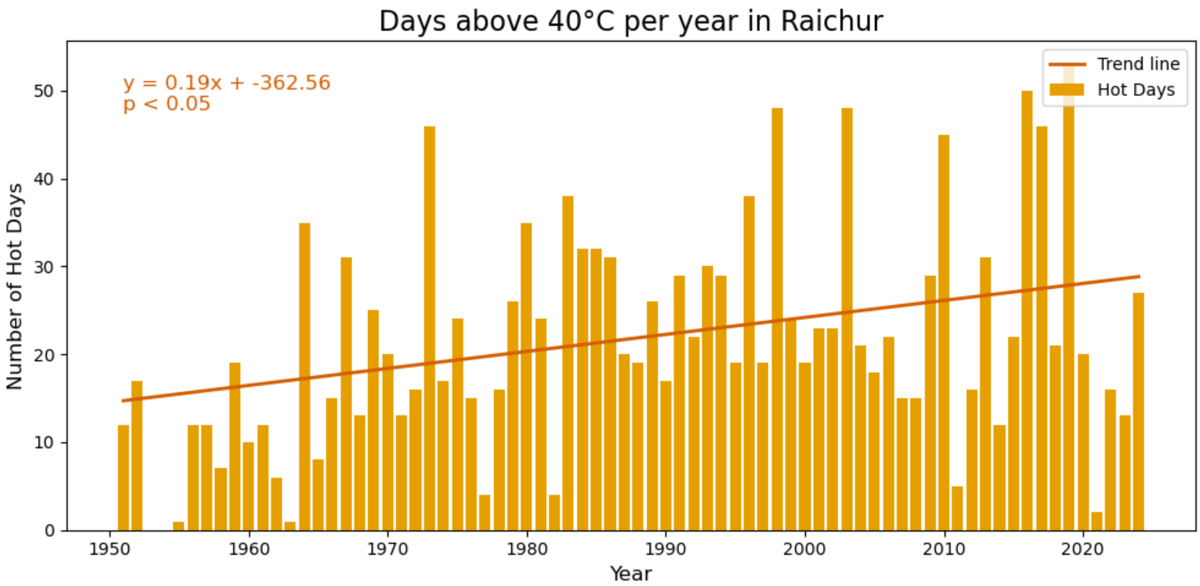


Figure 2. Number of hot days (>40°C) in Raichur with a trend line and the p-value for the significance of the rate of change.

3.1.1.2 *Hot streaks*

In Raichur (Figure 3. the top panel) the length of the longest hot streak of a year has significantly increased (9 days longer per 100 years). However, the number of hot streaks and the average length of such a hot streak have not significantly changed over time. For Chikkaballapur (Figure 3 on the bottom panel) however, not only the longest streak is increasing (20 days longer per 100 years) but hot streaks are also happening more often (3 more per 100 years) and their average length increased (7 days longer per 100 years).

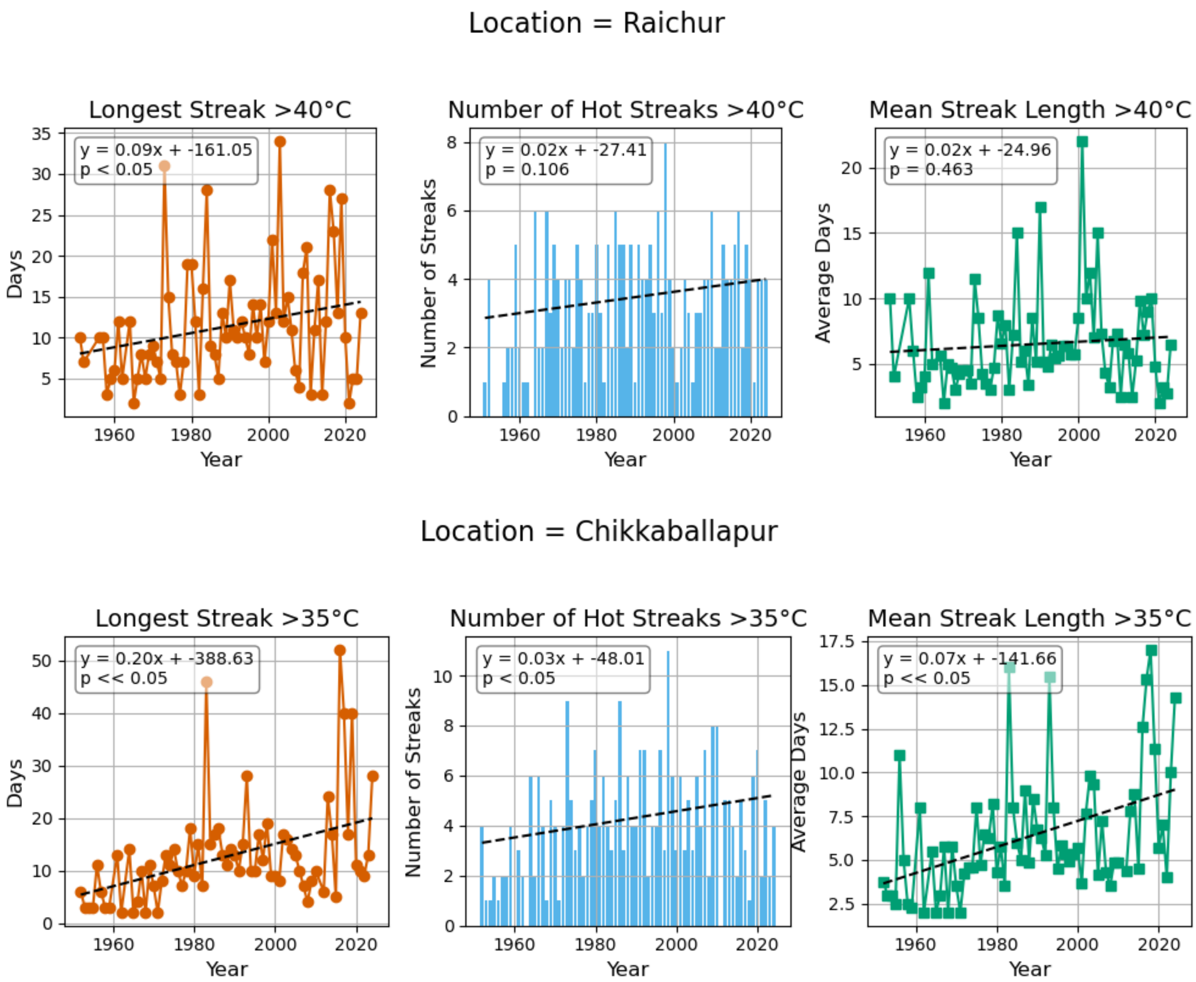


Figure 3. Longest hot streak (red), number of hot streaks in a year (blue) and a mean streak length (green) with a trend line, trend line equation and the p-value. for: Raichur (top) and Chikkaballapur (bottom).

3.1.1.3 *First and last occurrence of a hot day*

For the first hot day in Raichur we see that this occurs earlier in the year (see Figure 4). The hot days start earlier with a rate of 34 days per 100 years and has been found to be statistically significant. In 1951, the linear regression gives that we can expect the first hot day to happen around the 107th day of the year, which corresponds to the 17th of April. In 2024, it is expected to happen on day 82, corresponding to March 23rd. For Chikkaballapur, this first hot day occurs earlier with a rate of 28 days over 100 years. In 1951, this first day could be expected on day 101 (April 11th), and in 2024 it is expected on day 80 (March 21st). The changes for Chikkaballapur have also been found to be statistically significant.

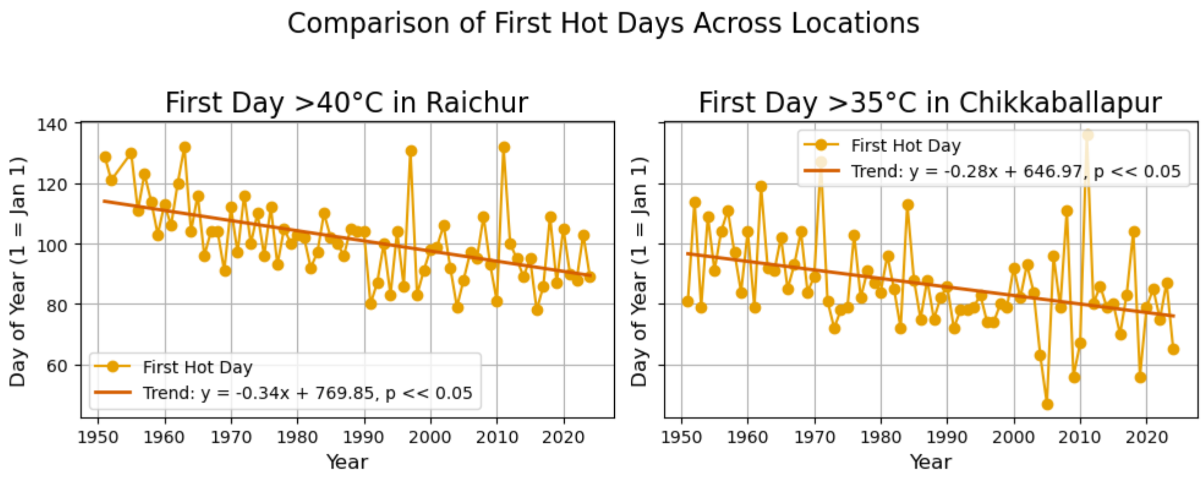


Figure 4. First occurrence of a hot day in a year (day of the year, yellow) with a trend line (orange), for Raichur (left) and Chikkaballapur (right).

The timing of the last hot day shows more nuanced change (see Appendix A). In Raichur, the final hot day has remained relatively constant at around day 150 (June 1), indicating that the hot season is now longer, beginning earlier but ending around the same time. In Chikkaballapur, the last hot day has shifted around 20 days earlier.

The timing of the last hot day shows less dramatic change:

- In Raichur, the final hot day has remained relatively constant at around day 150 (June 1), indicating that the hot season is now longer, beginning earlier but ending around the same time.
- In Chikkaballapur, the last hot day has shifted slightly later, from around May 18 in the 1950s to approximately May 25 in recent years.

Together, these patterns suggest a lengthening of the hot season, particularly in Raichur, with possible implications for water demand, heat-related livestock health issues, and labour conditions.

3.1.2 Temperatures during Rabi season

When comparing temperature distributions between the timeframe of 1951-1970 and 2005-2024 for the Rabi season, the following results are found (shown in Figure 5). As we can see from the frequency distributions, the temperatures seem to be moving towards more occurrences at higher temperature values for Raichur Tmax, Chikkaballapur Tmax and Chikkaballapur Tmin. For Raichur Tmin, we see a shift towards colder temperatures for the most recent data. More specifically, to start with the Tmin values of Raichur, this decreased with 0.22°C which is a significant result. Tmax changed with 1.03°C, and is also found to be statistically significant.

For Chikkaballapur, the mean temperatures for Tmin are found to have increased significantly between the two periods, with a change of about 0.22°C. The mean Tmax values experienced a greater shift of 1.04°C, which were also found to be significant.

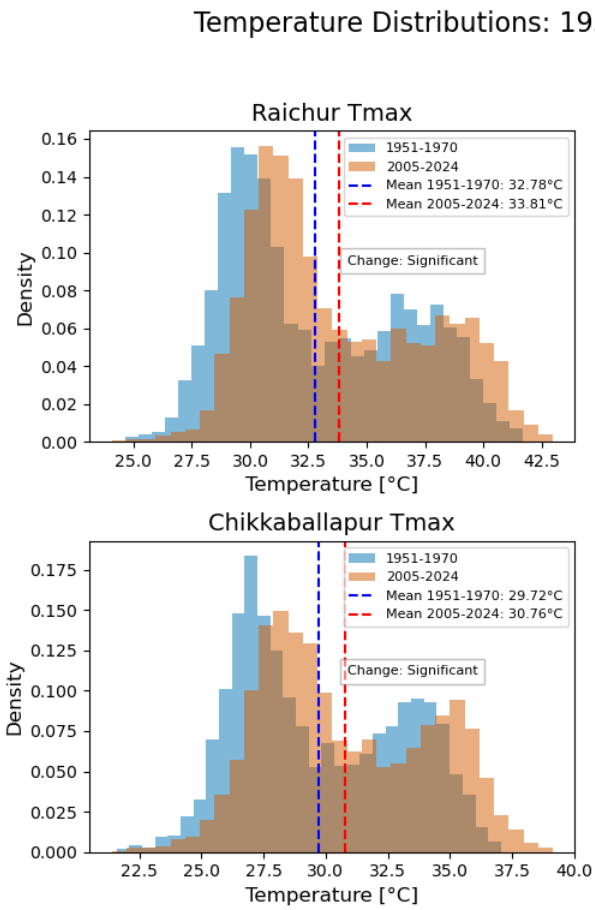


Figure 5. Probability distribution of Tmax and Tmin values in Rabi season in Raichur and Chikkaballapur in the time period of 1951-1970 (blue) and 2005-2024 (orange).

During the Kharif season, both regions exhibited a significant increase in maximum temperatures (Tmax) ($p<<0.05$), with Raichur and Chikkaballapur experiencing a rise of 0.56°C and 0.75°C, respectively. Minimum temperatures (Tmin) in Chikkaballapur also showed a significant increase of approximately 0.3°C ($p << 0.05$). Tmin in Raichur did not change significantly during the Kharif season ($p = 0.12$) (for more detail see Appendix A.)

Monthly analysis was conducted by comparing 20-year averages of Tmin and Tmax from the start (1951-1970) and end (2005-2024) of the dataset. The results show a clear warming trend in monthly maximum temperatures, with Tmax values from 2005-2024 consistently higher than those from 1951-1970 across all months in both regions (see Figure 6).

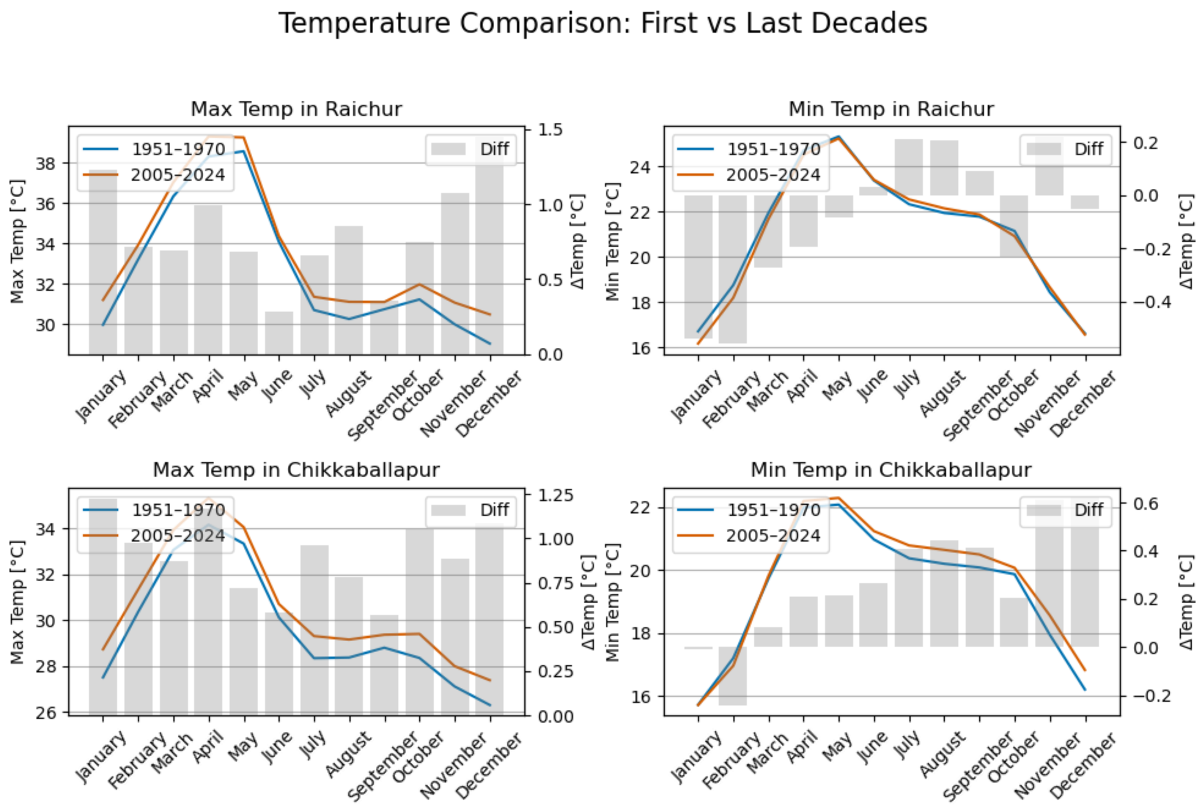


Figure 6. Mean monthly Tmax and Tmin values for the time period of 1951-1970 (blue) and 2005-2024 (red) and the difference between those values (grey). Tmax and Tmin values for Raichur and Chikkaballapur.

3.1.3 Main findings

This section summarises the most relevant trends from the temperature data analysis:

Extreme Heat is Becoming More Frequent

- The number of hot days (Tmax > 40°C in Raichur, > 35°C in Chikkaballapur) has increased significantly, with the frequency of hot days increasing faster for Chikkaballapur.
- Hot streaks (consecutive hot days) are getting longer (average and maximum length) in Chikkaballapur. In Raichur, only the duration of the longest hot streak in a year increases significantly.
- The onset of hot days has shifted to earlier in the year by about 4 weeks, reducing the safe window for early-season crop activities and increasing early heat stress risks for both districts.

Minimum and Maximum Temperatures Trends

- While Tmax has increased consistently, Tmin trends are region- and season-specific:
  - Chikkaballapur: Slight increase overall, with some months showing cooling.
  - Raichur: Tmin is relatively stable or decreasing, contributing to rising DTV.
- Warming is more pronounced in the cooler months, especially during the Rabi season (winter cropping) in Chikkaballapur.

- Tmax temperatures rise faster than Tmin temperatures in Rabi season.
- Rising Rabi temperatures could reduce yields by disrupting crop development, flowering, or chilling requirements.

Rabi Season Warming is a Major Agricultural Threat

- Chikkaballapur shows a 1.05°C increase in Tmax and 0.2°C in Tmin during Rabi season.
- Raichur shows a similar increase in Tmax but a decline in Tmin, leading to increased DTV.

Timing of Critical Heat Events is Shifting

- First hot day now occurs about 4 weeks earlier, while the last hot day has remained stable (Raichur) or is also occurring earlier in the year (around 20 days earlier for Chikkaballapur)
- This lengthens the duration of the hot season, increasing cumulative heat stress, irrigation needs, and labour risks.

3.2 RAINFALL

In this subchapter the results of the rainfall critical climate-stress analysis will be discussed. These chapters have been put in the order of the months that they occur in. Therefore, The Rabi season is discussed first, followed by the onset of the Kharif season. Subsequently the critical climate stress moments that take place during this season are discussed in the order of, heavy rainfall, dry spells in July and August and heavy rainfall in September and October. Lastly, yearly trends of rainfall intensity and drought years are discussed. The end of this subchapter includes the main findings related to the temperature rainfall data analysis.

3.2.1 Onset Kharif

The onset of the Kharif is defined as the first day after June 1st that there has been more than 70 millimetres of cumulative rain. This is based on there being sufficient rain for sowing purposes. A delayed onset of the Kharif leads to a shorter growing season, resulting in crop losses or farmers being forced to change crops.

The historical analysis of the onset of the Kharif in Raichur shows that over time the Kharif starts earlier (see Figure 7). Over a time period of 100 years, the Kharif begins 6 days earlier ($p<<0.05$). This could mean that farmers can move their sowing period forward in time in order to maximise yield. Similarly to Raichur, the Kharif seasons also starts 6 days earlier over a 100-year period for Chikkaballapur ($p<0.05$) (Figure 8).

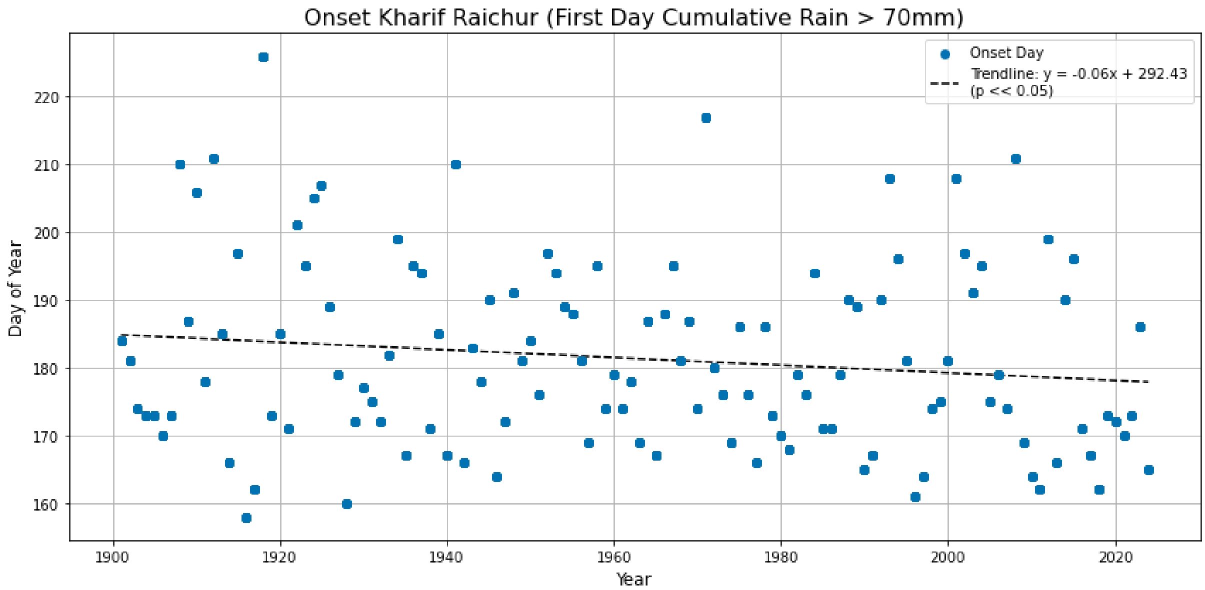


Figure 7. Onset of Kharif season in Raichur.

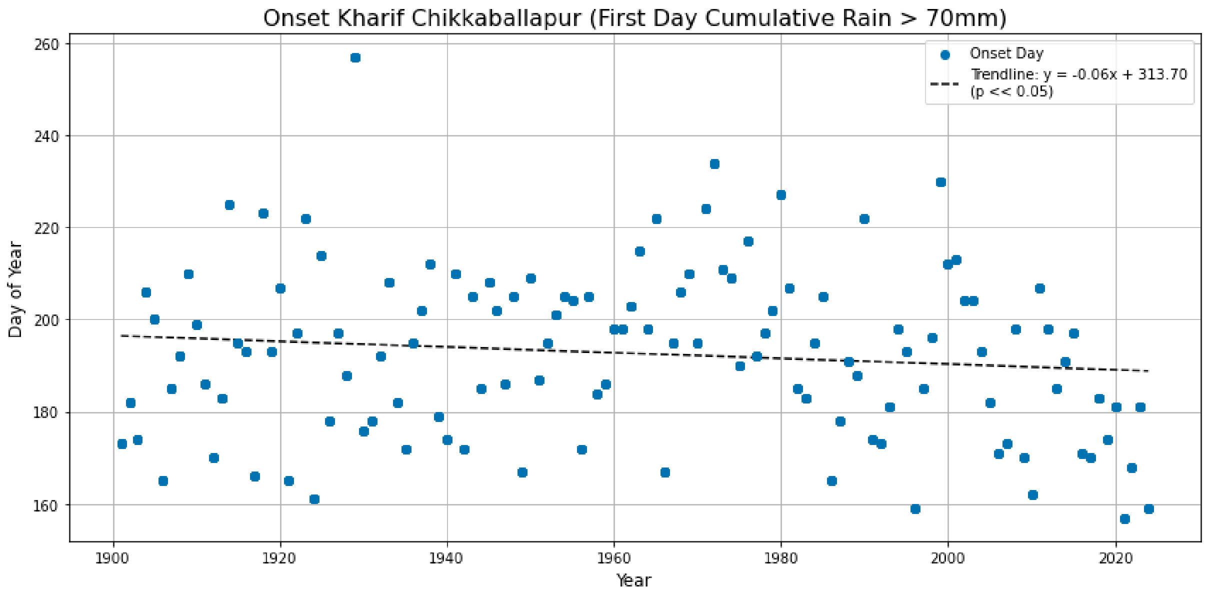


Figure 8. Onset of Kharif season in Chikkaballapur.

3.2.2 Heavy rainfall

In Raichur, the peak of heavy rain days in corresponds with the year of highest annual rainfall (Figure B1), indicating that extreme rainfall events can influence the total annual rainfall. The black dashed trendline shows upward slope, indicating gradual increase in the frequency of heavy rainfall events overtime (Figure 9).

In Chikkaballapur, the extremes are less pronounced than those in Raichur. The trendline remains relatively flat with a small positive slope, suggesting that the number of heavy rain days mostly stable with only slight increase over the periods (Figure 9).

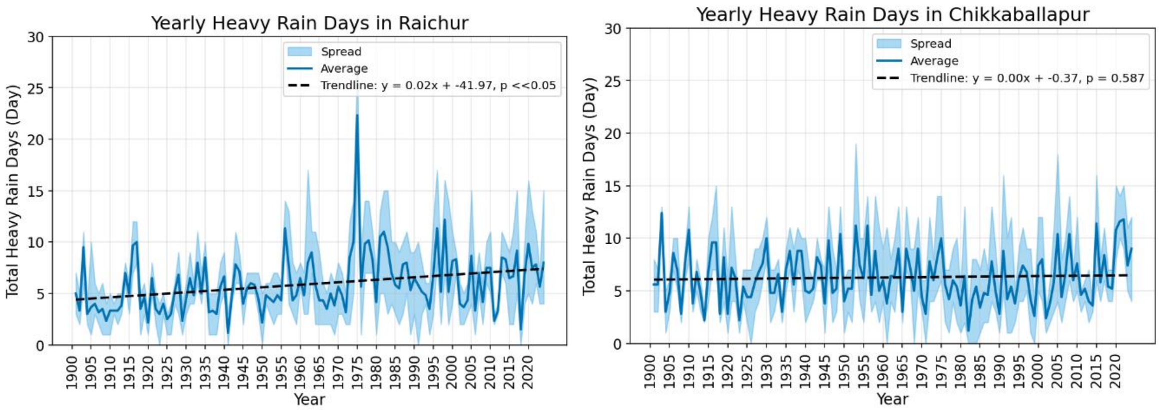


Figure 9. Yearly heavy rain days in Raichur and Chikkaballapur between 1901 – 2024. The blue shaded represents the spread of annual rainfall of each coordinate.

3.2.3 Dry spells

For both Raichur and Chikkaballapur the occurrence and duration of dry spells can be viewed in Figure 10. There is no significant evidence to indicate a change in frequency of dry spells between the first 30 and last 30 years, for either region. Furthermore, there is no significant evidence for a change in the length of the dry spells in either Raichur or Chikkaballapur between the first 30 years and the last 30 years. More detailed information on the occurrence and length of these dry spells is located in Appendix C (Tables C1 and C2).

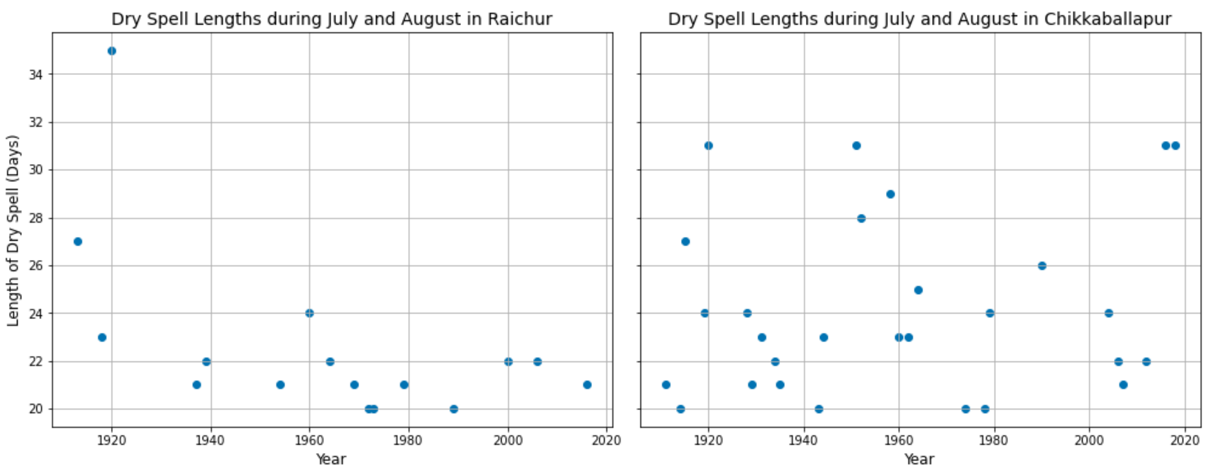


Figure 10. Dry spell lengths during July and August in Raichur and Chikkaballapur.

3.2.4 Rainfall September and October

For Raichur, the amount of rainfall in September and October shows an increase of 17 and 29 millimetres over a period of 100 years, according to the linear regression (Figure 11). However, these changes are not statistically significant therefore it is not possible to state whether farmers can expect more rainfall during these months.

For Chikkaballapur, historical data does not show any statistically significant change in the amount of rainfall during September and October (Figure 12). Albeit not significant, the amount of rainfall in September does show a decline over time. This is about 19 millimetres over a period of 100 years. October, however, shows an increase of rainfall throughout time of 10 millimetres over a period of 100 years.

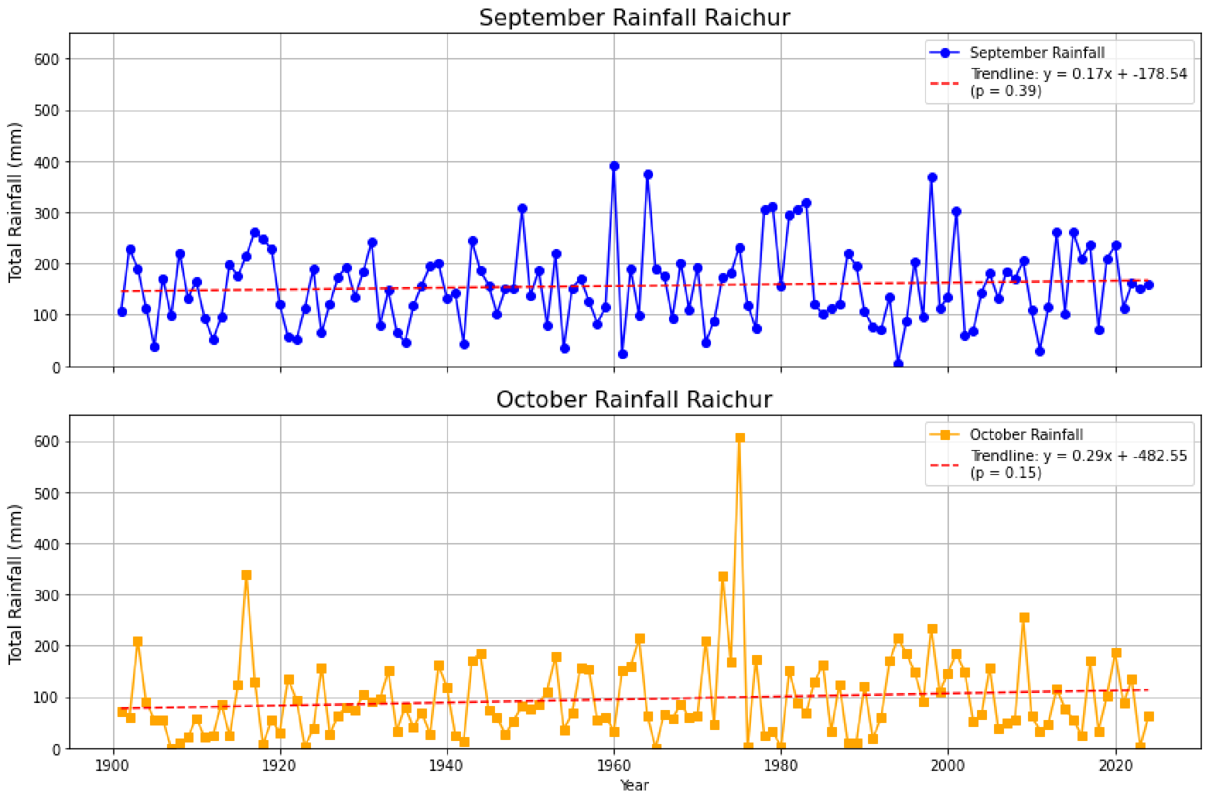


Figure 11. Total rainfall of September and October in Raichur.

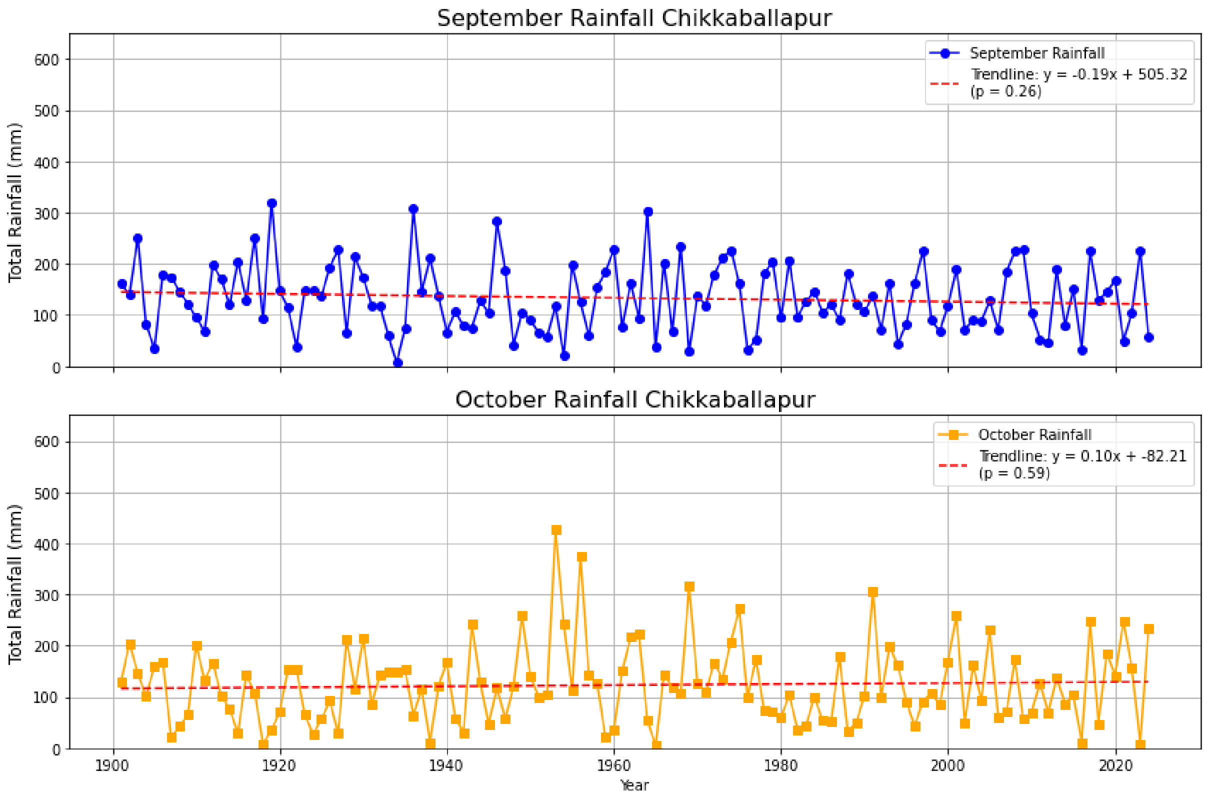


Figure 12. Total rainfall of September and October in Chikkaballapur.

3.2.5 Rainfall intensity

For Raichur the average annual rainfall intensity of rainy days has increased with an extra 3 millimetres of rainfall on a rainy day per 100 years (Figure 13, top panel). For Chikkaballapur there was also an increase, but with 1 millimetre extra per rainy day every 100 years (FIgure 13, bottom panel). For Raichur the p-value is <<0.05 and for Chikkaballapur it is < 0.05.

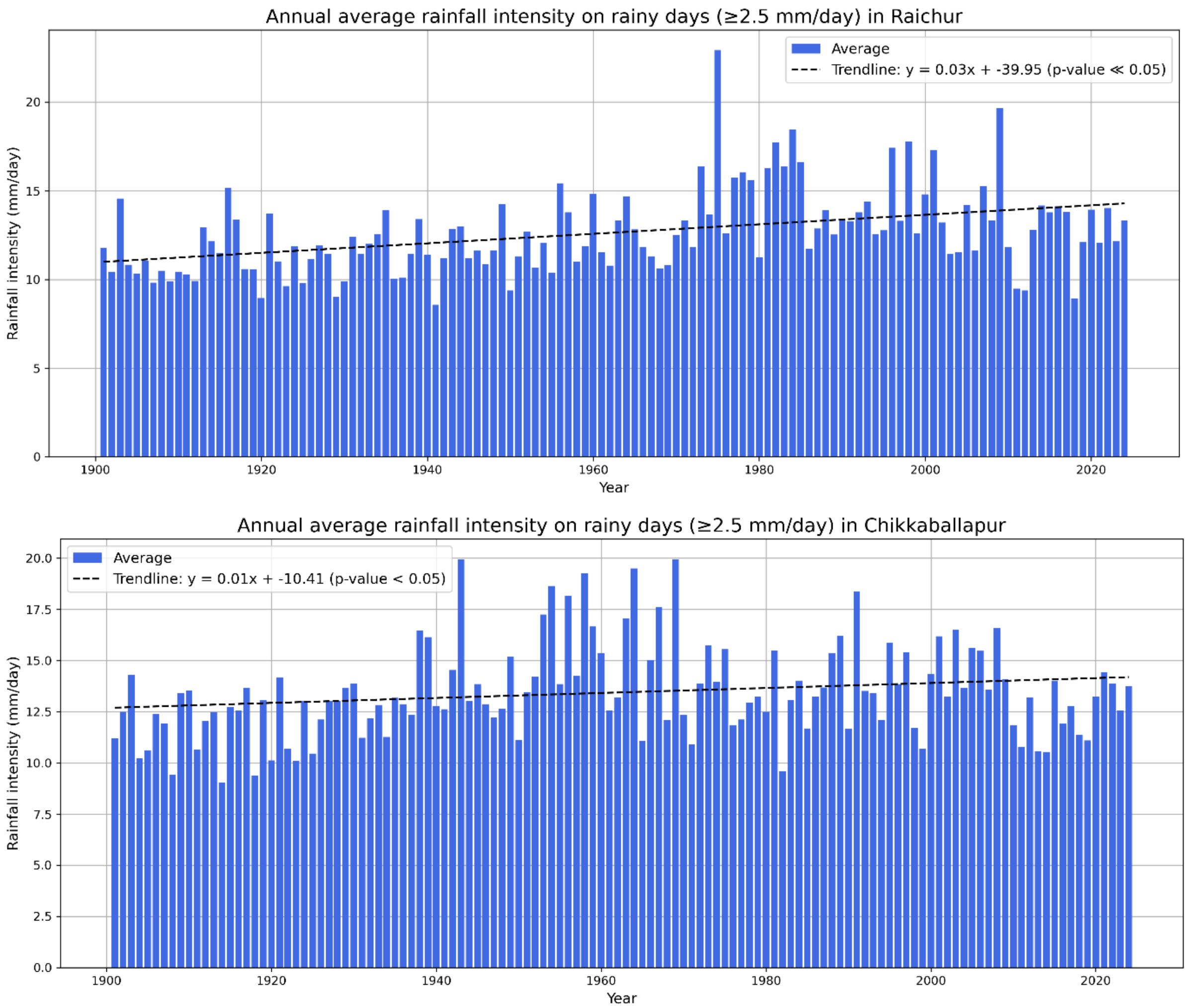


Figure 13. Annual rainfall intensity on rainy days (≥2.5 mm/day) in Raichur (top) and Chikkaballapur (bottom), averaged over all data points.

The monthly rainfall intensity compared between the representative climate periods show for Raichur that the rainfall intensity has increased between March and November while it has decreased in the remaining months (Figure 14, top panel). However, statistical significance is only observed for the months March-June and September. For Chikkaballapur the rainfall intensity has increased in the months February, April-August, October and December while it decreased in the remaining months (Figure 14, bottom panel). However, statistical significance is only observed in May and August.

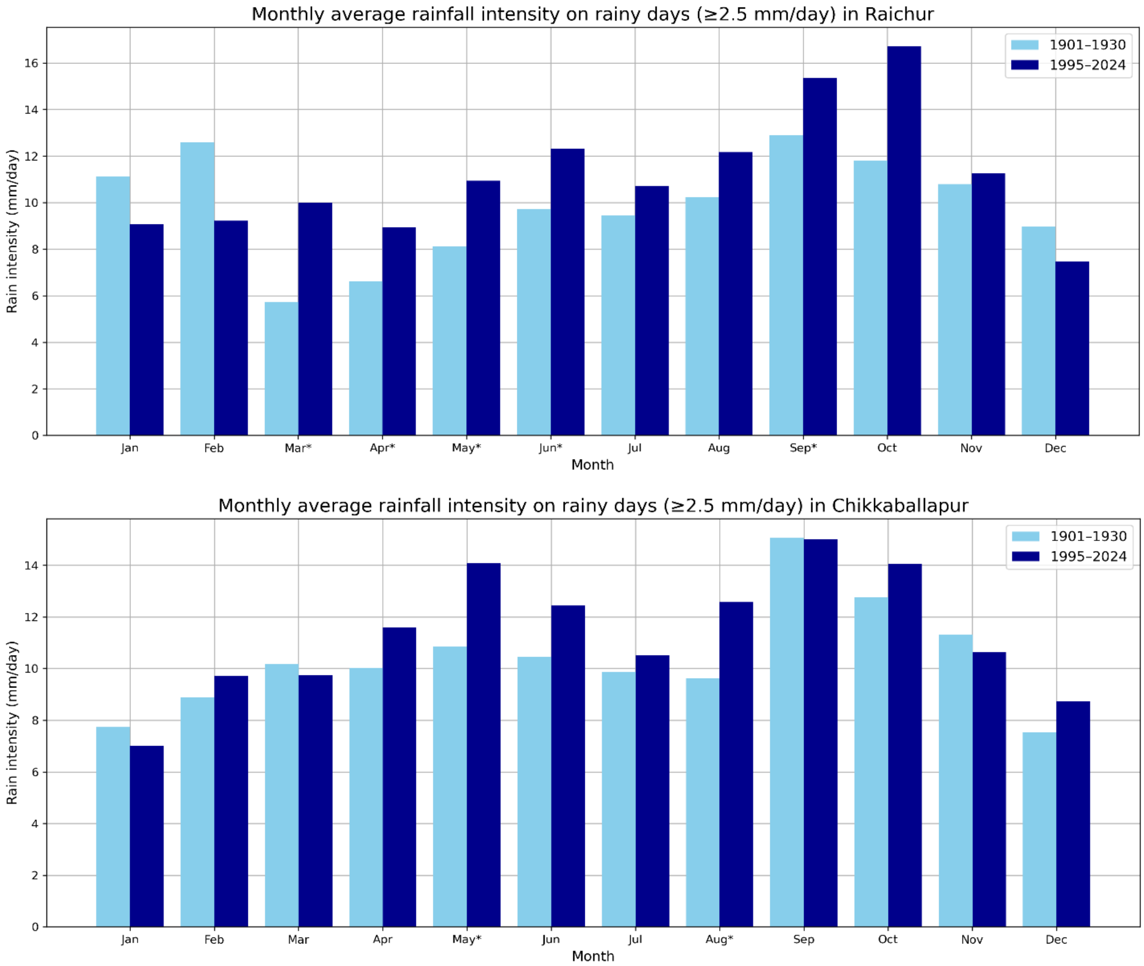
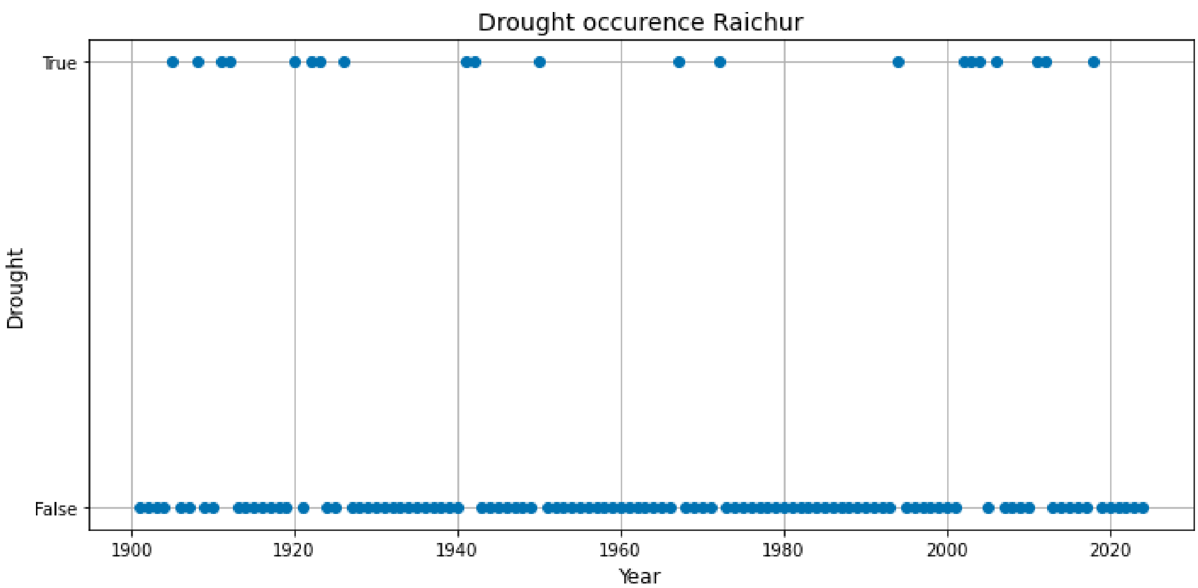


Figure 14. Monthly rainfall intensity on rainy days (≥ 2.5 mm/day) in Raichur (top) and Chikkaballapur (bottom), averaged over all data points and data years. An asterisk means a significant result (p-value < 0.5).

3.2.6 Drought years

Both Raichur and Chikkaballapur have experienced several droughts between 1901 and 2024 (Figure 15, Raichur, top panel; Chikkaballapur, bottom panel)).



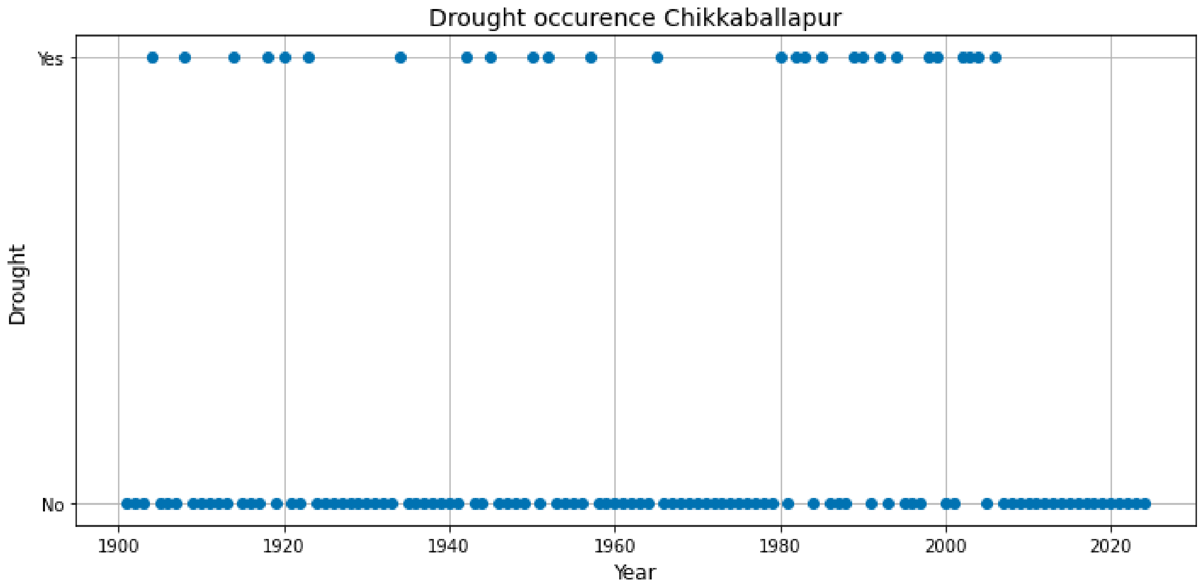


Figure 15. Drought occurrence in Raichur (top) and Chikkaballapur (bottom).

The frequency of droughts changed over time (Tables C3 and C4). Compared to the representative climate period of the dataset there are several 30-year periods with statistically significant different frequency of droughts in Raichur (Table 3) and Chikkaballapur (Table 4). In Raichur there has been 44-time windows of 30 years in which there were significantly fewer droughts compared to the first 30 years. Recent years show no significantly different results therefore one cannot conclude that the frequency of droughts is changing over time.
However, for Chikkaballapur there is one period of consecutive time windows with significantly different amounts of droughts. 30-year windows starting from 1973 till 1985 show significantly more droughts than the representative climate period. These results do not indicate a significant trend in the frequency of droughts.

Table 3. Significantly different frequency of drought than representative climate period in Raichur.

Start year	End year	Duration	More/fewer	Significance
1927	1937	11	Fewer	<0.05
1942	1974	33	Fewer	<0.05

Table 4. Significantly different frequency of drought than representative climate period in Chikkaballapur.

Start year	End year	Duration	More/fewer	Significance
1973	1985	13	More	<0.05

3.2.7 Main findings

Rainfall Patterns and Trends

- Rainfall during the Rabi season has shown no change in both Raichur and Chikkaballapur
- Kharif season now begins, on average, 6 days earlier than it did 100 years ago in both regions.
- No changes were observed in rainfall during September and October for either region.

Heavy Rainfall Events

- In Raichur, the number of days with heavy rain has increased with 2 days over a period of 100 years.

- In Chikkaballapur, the number of days with heavy rain has not changed.

Rainfall Intensity

- In Raichur, rainfall has gotten more intense between March-June and September
- For Chikkaballapur rainfall has gotten more intense in May and August.

Dry Spells and Droughts

- The frequency and duration of dry spells have not changed in either region
- No changes were observed in drought patterns for both Raichur and Chikkaballapur

4. Comparative analysis

4.1 Comparison of 0.1° and 0.25° spatial resolutions of rainfall datasets in Raichur and Chikkaballapur

The comparison between the IPED dataset (0.1° resolution) and the IMD dataset (0.25° resolution) across 2 coordinates for Raichur and Chikkaballapur from 1991 – 2023 is illustrated in the scatter plot in Figure 16. Each point represents the average of total annual rainfall across all coordinates for a given year in each region. Both regions show strong positive relationship between two datasets, as indicated by high Pearson correlation coefficient (r=0.82 for both region) and the correlation is statistically significant ($p<0.05$, while the root mean square error (RMSE) values is 206.55 mm/year and 206.27 mm/year for Raichur and Chikkaballapur, respectively. The left panel shows that for Raichur (1.01x) the datasets have very similar annual values on average whilst in Chikkaballapur there is a disparity (0.78x).

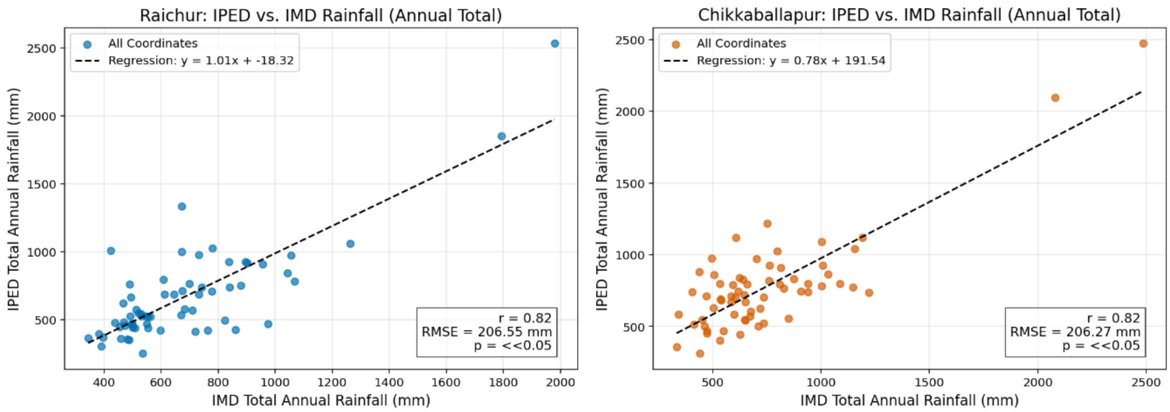


Figure 16. Scatter plot of total annual rainfall between 0.1° and 0.25° spatial resolution data in Raichur and Chikkaballapur.

Rainfall variability in Rabi and Kharif season for Raichur and Chikkaballapur shows in Table D1. In the kharif season, correlation is generally strong which ranging from 0.77 – 0.91, indicating that IPED data closely aligns with IMD data during this high-rainfall period. While RMSE percentage value for Kharif season is relatively low. In contrast, the Rabi seasons shows weaker correlation with a higher RMSE and percentage RMSE value.

The comparison of total annual rainfall between 0.1° IPED data and 0.25° resolutions IMD data for Raichur and Chikkaballapur shows notable patterns in Figure 17. In Raichur, at both coordinates, the medians of IMD and IPED rainfall are quite similar, indicating general agreement in average rainfall values. However, the IPED data shows a slightly wider interquartile range, especially at 16.5, 77.00, suggesting larger variability in IPED dataset. In Chikkaballapur, a similar pattern emerges. Although the medians of IPED rainfall are slightly higher than that of IMD rainfall. The IMD rainfall data of Chikkaballapur shows more outliers.

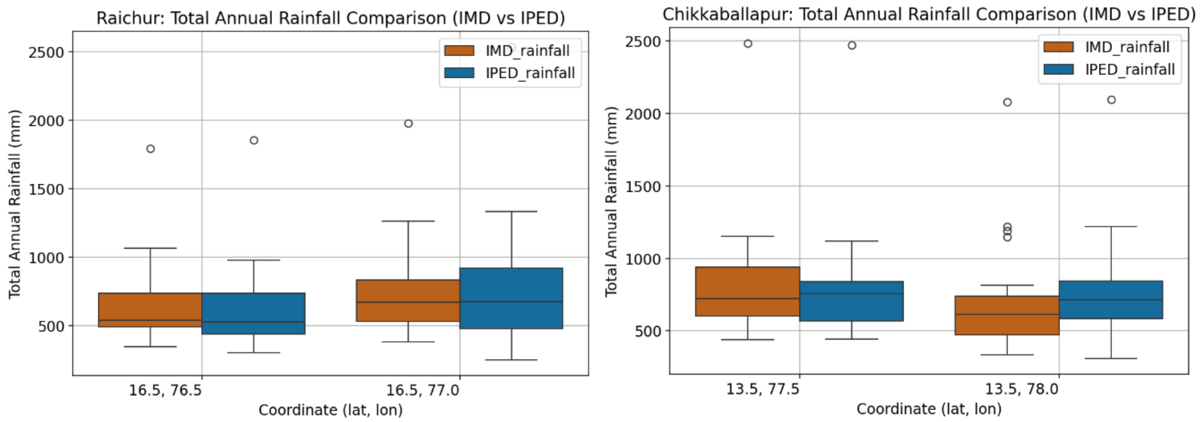


Figure 17. Comparison of total annual rainfall of 0.1° and 0.25° spatial resolution in Raichur and Chikkaballapur.

4.2 Comparison of observational and gridded rainfall datasets in Raichur

The comparison between observed and IMD rainfall data across six stations in Raichur region from 2000-2016 is visualised in Figure 18. Each point represents the annual total rainfall for a given station and year, with observed values on the x-axis and corresponding IMD values on the y-axis. The Pearson correlation coefficient of r = 0.66 indicating a positive relationship between two datasets and this correlation is statistically significant ($p<0.05$), while the RMSE is 165.08 mm/year. Overall, the regression indicates that the IMD data provides reasonable approximation of annual observed rainfall at the station, although notable variability is observed across stations.

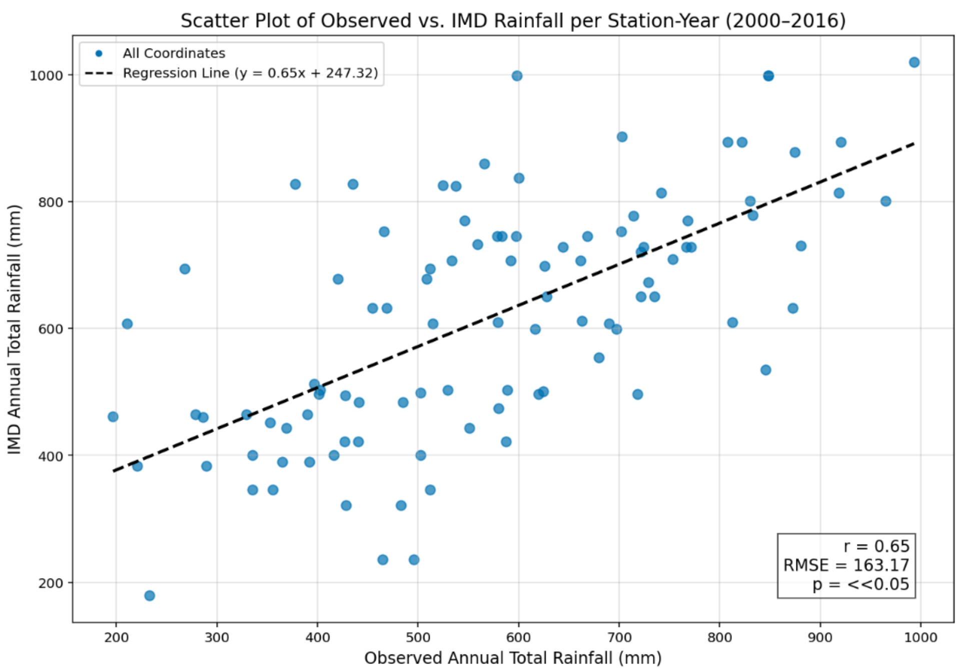


Figure 18. Scatter plot of annual rainfall of Observed and IMD data in Raichur.

To gain further insight into the rainfall variability, seasonal comparisons were performed using all available years for each station. The result shown in Table D2 displays clear differences between the Rabi and Kharif season. In general, rainfall in the Kharif exhibits higher correlation values and lower percentage error. In contrast, rainfall in Rabi season tends to show weaker correlations and larger percentage error. This may be due to the lower rainfall amount and less stable pattern of rainfall in Rabi compared to Kharif season.

Comparison of total annual rainfall between the observed and the gridded dataset across multiple stations in Raichur is showed in Figure 19. The IMD data generally exhibits higher median and interquartile ranges, indicating a wet bias and a tendency to overestimate rainfall. The observation data in Deodurga stations showed greater variability and notable outliers, suggesting it captures a broader range of rainfall values than the IMD dataset.

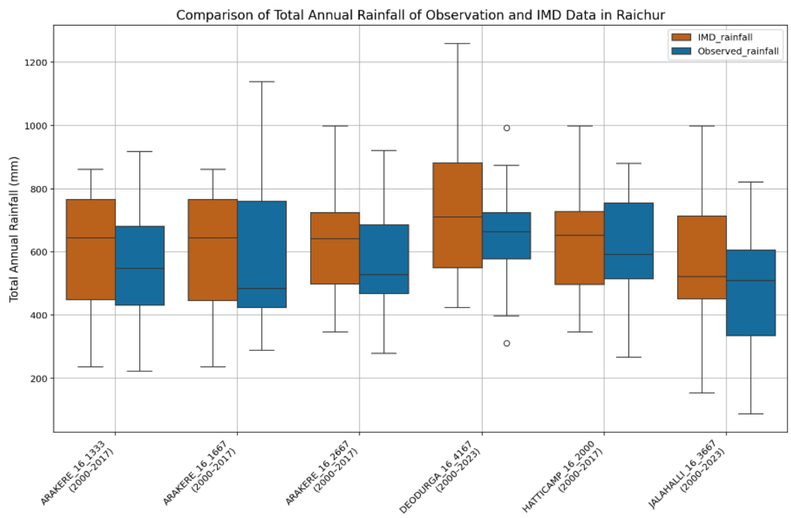


Figure 19. Comparison of total annual rainfall between observed and IMD data in Raichur.

5. DISCUSSION

The goal of this project was to identify historical trends in agricultural relevant critical climate-stress moments for Raichur and Chikkaballapur in Karnataka, India. By analysing long-term historical temperature and rainfall datasets, the project has provided insight into the shifting climate patterns, but the results have to be interpreted through the lens of the data quality and methodology limitations. This section discusses those limitations of the analysis, as well as potential areas to develop further.

The onset of the Kharif season is getting earlier based on our data, while the general assumption of this critical climate-stress moment is that it is delaying. This requires further research to validate the result and check whether this is the case in more regions. The critical climate stress moments thresholds were designed for agriculture in different regions than the ones analysed. Therefore not every critical threshold was applicable to the study regions. Temperatures in Chikkaballapur do not exceed the critical threshold of 40°C, instead the threshold was based on the corresponding percentile in Raichur for 40°C. This does mean that any changes in the hot streaks in Chikkaballapur concern very hot days for this region but not the critical threshold for agricultural practices.

The timespan chosen as the representative climate period for the temperature data covers 20 years rather than the standard 30-year period in climate sciences. This does come with its limitations but due to the size of the dataset (70 years) it was decided upon that 20 years covers most natural variability in the climate system and yet allows enough time between the time periods to be able to compare them.

Statistical tests were performed using a conventional p-value threshold of 0.05 to determine significance. However, the choice of threshold was arbitrary. A less conservative threshold (e.g., 0.1) would lead to more findings being deemed significant.

All gridded datasets used in this project are reanalysis data, meaning they are modelled data validated with observations. While this ensures consistency over space and time, it also introduces model bias and uncertainty, especially in regions with low data availability. As models have tendency to project average trends, this can lead to a loss of extreme values and propagation of model bias in the analysis. The temperature data was available at a spatial resolution of 1° (approximately 100 km), resulting in only a single grid point covering each region. This coarse resolution misses significant spatial heterogeneity, especially in areas like Chikkaballapur with topographic variation (e.g., elevation gradients). As such, the identified temperature trends may not fully capture local stress conditions that farmers in different parts of a region experience.

The comparative analysis showed that the IMD dataset overestimated the amount of rainfall compared to the observed rainfall dataset. However, the compared points were matched on shortest distance and were therefor not located in the same location. This could explain the observed differences between the datasets. Additionally, the observational dataset originally consisted of eight stations but only six were analysed. The other two were omitted due to their values contradicting each other whilst being located at the same coordinate.

6. CONCLUSIONS

This project aims to support WELL Labs by analysing historical temperature and rainfall data to identify changes in critical climate-stress moments in Raichur and Chikkaballapur, within the agricultural context. The findings will contribute to the CLARITY project. The central research question is: *What historical trends, regarding critical climate-stress moments in agriculture, can be observed in Raichur and Chikkaballapur, India, based on:*

- *temperature data between 1951 and 2024?*
- *rainfall data between 1901 and 2024?*

The project also includes comparisons between modelled rainfall data at 0.1° and 0.25° spatial resolutions, and between observed station data and 0.25° IMD modelled data for Raichur.

A comparative analysis was conducted between the IMD dataset, IPED dataset and observed station rainfall data. The finding shows that the IPED (0.1°) and IMD dataset (0.25°) are highly correlated in Raichur and Chikkaballapur, particularly during the Kharif season with the high-period rainfall. When comparing IMD rainfall data with observed station data, the IMD generally captures the overall rainfall well but tends to overestimate the annual amount of rainfall compared to ground-based observation.

Rising mean temperature trends have been identified in both Raichur and Chikkaballapur. This warming trend coincided with the increase of the number of hot days (defined as days with recorded temperatures above 40°C for Raichur and 35°C for Chikkaballapur). Hot streaks, defined as consecutive hot days have been found to get longer for both regions, with Chikkaballapur also reporting a rise in the frequency of such streaks.
Hot days now occur, on average, about two weeks earlier in the year than they did 70 years ago. That leads to an increased time window where agricultural systems are exposed to heat stress. Increase in the number of hot days, especially days exceeding 40°C has been found to severely impact agriculture, both the crops and animals (Srinidhi et al., 2024). Consecutive hot days might be even more detrimental to agriculture, as they cause a more cumulative stress (Joshi et al., 2020).
Another significant temperature-related climate stress is the increase in the Rabi season temperatures. Both regions experience an increase in the Rabi temperatures, which are rising faster than Kharif temperatures. This change in a climate pattern might negatively impact especially Rabi crops (Srinidhi et al., 2024).

For precipitation in Raichur the rainfall seems to be getting significantly more intense between March-June and September. For Chikkaballapur only significant changes have been found for May and August where the rainfall increases in intensity. We can conclude this climate stress is getting more severe based on historical data. The number of days with the most intense rain (above 25 mm of rainfall per day) are increasing for the region of Raichur, and no significant change for Chikkaballapur.
The analysis on dry spells did not show statistical significance for change in either the length or the frequency of occurrence, this is the case for both Raichur and Chikkaballapur. This is also the case for drought years overall, which do not seem to be significantly increasing.

The only climate stress that seems to be getting a smaller issue is the delayed onset of Kharif, which shows very high statistical significance to arrive earlier. It is estimated to arrive 6 days earlier every 100 years for both regions. Kharif does seem to be getting more rainfall in its entirety, which could have been concerning if this was happening later in the season around September and October. However, when looking at these months specifically no statistically significant result of an increase in rainfall has been found.

7. RECOMMENDATIONS

Based on the temperature and rainfall results that have been discussed with Janapara and Prarambha the following recommendations, considering future research, are proposed.

Firstly, we recommend doing more crop specific research in addition to the general climate trends. This could give farmers a better idea which crop is suitable for their region and climate. Next to crop specific thresholds, the days after sowing for recent years can be investigated for different crops as well. This can give some more insights for the most crucial periods of the year and could give some areas to improve in for lower climate/yield loss risks. For the most direct results to the local farmers we recommend a predictive tool, such as a crop calendar, to help farmers make decisions on what and when to sow or harvest.

For more insight in local changes, we feel farmers are very interested in zooming into the last decade. Even though we understand how this makes sense from their perspective, we strongly advice to be careful with this analysis and keep natural variability of the climate system in mind. This to avoid putting measures in place, that will only work every couple of years. To counter this unpredictability, it could be insightful to look further into the natural climate cycles that apply locally, to possibly correct for the variability and make more specific recommendations to farmers possible.

During the meeting with Prarambha, additional datasets have been mentioned to be available. This is mostly concerning hydrological measurements or additional meteorological data. Depending on what is available a higher spatial and temporal resolution can be used. For instance, with our current data we were not able to look at the heavy hourly rainfall as a critical climate stress moment, which is something that can be considered investigating with a higher temporal resolution.

As we have seen from the analysis and comparison for Chikkaballapur and Raichur, there are some similarities, however still some variables had very different results. Therefore, we advise looking into neighbouring districts before using this information to guide decisions in other areas. Especially as temperature and rainfall are very much interlinked, and therefore have very different effects in different areas. Further research could determine the strength of the connection, for example in the months where increasing temperatures coincide with a decrease in rainfall and vice versa, a further day by day analysis can be useful. We recommend more research on how crops and livestock react to multiple variables changing at the same time.

Then, not only the livestock and crops are important when looking at climate stress factors, worker health impacts are vital to consider as well. Especially with the increasing temperatures, we recommend looking further into renewing/making safe working guidelines.

Overall, we would recommend continuing the stakeholder involvement throughout the process as this leads to the results that are most useful to the communities that need it the most.

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Declaration of AI usage

Generative Artificial Intelligence (AI) has been used in the process of this project. AI was primarily used for understanding and resolving errors in the Python scripts, created and used during the analysis. Additionally, AI, in the form of Grammarly, has occasionally been used to check for grammatical errors. At all times were the researchers critical of the outputs of AI and have the results been checked. The authors take full responsibility for the content of the publication.

APPENDICES

APPENDIX A – ADDITIONAL TEMPERATURE DATA ANALYSIS

Temperature data analysis

Temperature is vital to agricultural productivity and stability, with crops and livestock adapted to specific seasonal temperature ranges and patterns. However, climate change, driven by greenhouse gas emissions is disrupting these patterns (Joshi et al., 2020). As an example, in semi-arid regions like Raichur and Chikkaballapur (Karnataka, India), extreme heat events and warming winter temperatures are becoming more noticeable (see section 3.1.2 in the main text). Temperatures above 40 °C threaten crop yields, livestock health, and labor productivity, while rising winter temperatures are reducing Rabi crop yields (Srinidhi et al., 2024).

General temperature trends

Mean daily temperatures (Tavg) have increased significantly in both regions ($p \ll 0.05$). Raichur has warmed by approximately 0.35 °C, reaching a current mean annual Tavg of 27.2 °C. Although Chikkaballapur remains cooler overall, its rate of warming is higher: the mean annual Tavg increased by 0.5 °C, reaching 24.6 °C. The rate of warming, based on the slope of the linear regression of annual average Tavg (see Figure A1), is estimated at +0.007 °C/year for Raichur and +0.012 °C/year for Chikkaballapur.

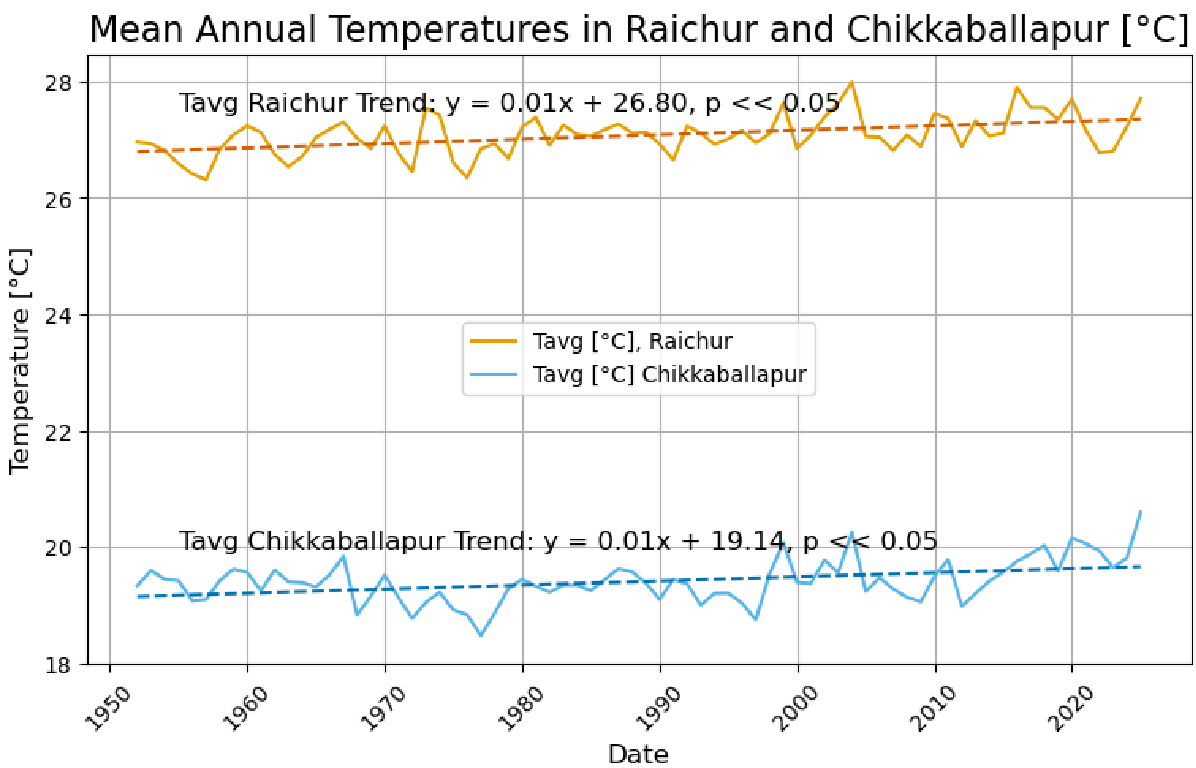


Figure A1. Mean annual temperature in Raichur (orange) and Chikkaballapur (blue) over the years. In both location an increase in the mean annual temperatures were observed, with Chikkaballlapur temperature rising faster (trend line for Raichur, yellow) (trend line for Chikkaballapur, red).

Maximum daily temperatures (Tmax) are increasing at a significantly faster rate than minimum daily temperatures (Tmin) in both regions ($p \ll 0.05$). This trend aligns with the increasing frequency and intensity of heat-related climate stresses, particularly the rise in days where temperatures exceed critical thresholds (see section 3.1.2 in the main text and Figure A2). On average, Tmax has risen by approximately 0.7–0.8°C in both regions (see Table A1). For more detail of the temperature change see Table A2 (for Raichur) and Table A3 (for Chikkaballapur). The annual rate of increase for Tmax is +0.014 °C/year in Raichur and +0.016°C/year in Chikkaballapur, supporting the observation of a stronger warming trend in average temperatures (Tavg) in Chikkaballapur. Tmin, in contrast, appears relatively stable, showing much smaller changes compared to Tmax. In Raichur, the mean Tmin remained constant over the years, while in Chikkaballapur, it increased by roughly 0.2°C ($p << 0.05$) (see Figure A2). For the change in probability distribution of Tmax and Tmin in both regions in the representative climate and now, see Figure A5.

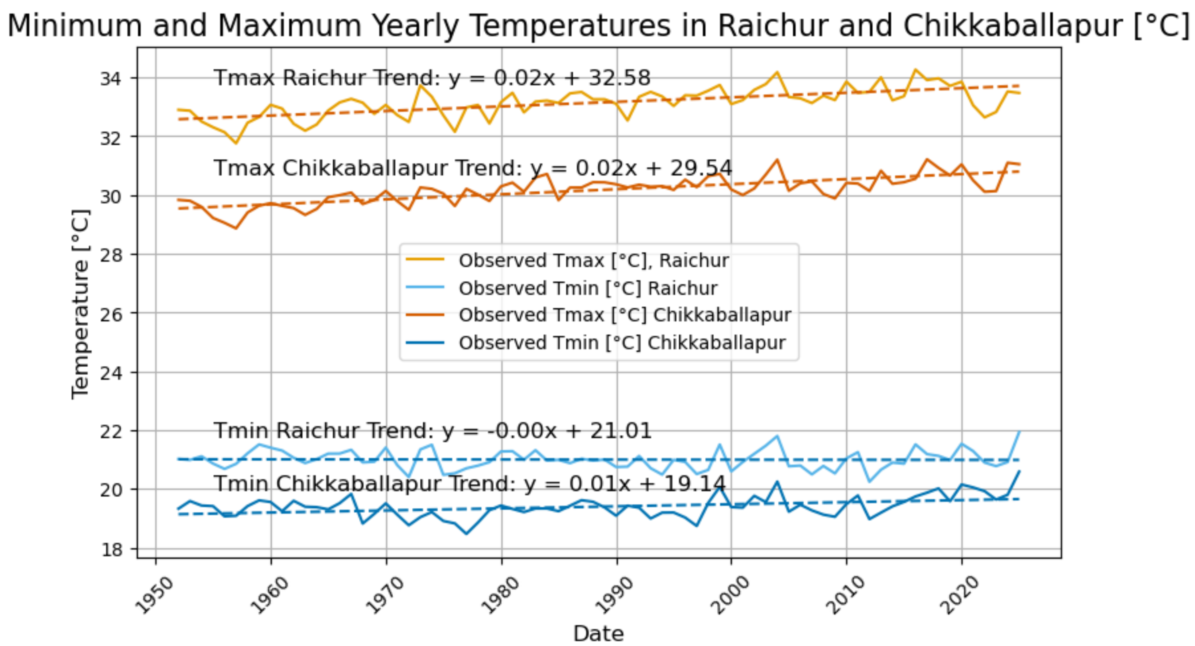


Figure A2. Mean annual Tmin and Tmax values in Raichur and Chikkaballapur over the years with trend lines.

Diurnal Temperature Variation (DTV) increases significantly in both regions: +0.015 °C/year in Raichur and +0.009 °C/year in Chikkaballapur ($p << 0.05$). Both region show a significant variation in DTV in a yearly cycle, with the highest DTV in winters, and lowest in summers (see Figure A3)

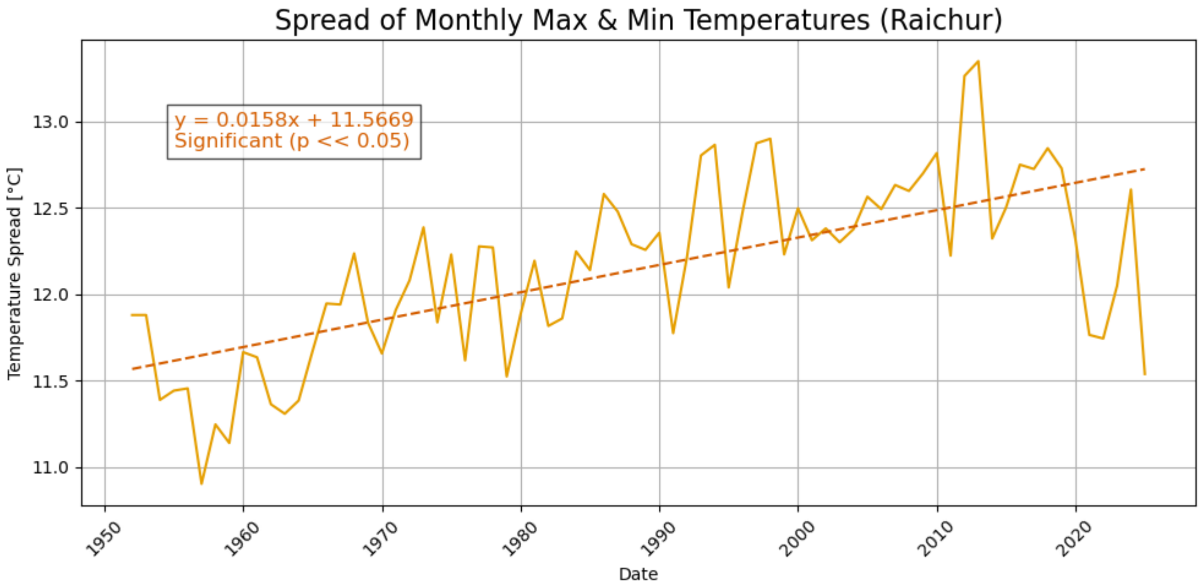


Figure A3. Monthly DTV in Raichur for the analysed period with a trend line. Monthly DTV is increasing significantly. This is linked, to the faster rate or warming days (Tmax) than nights (Tmin).

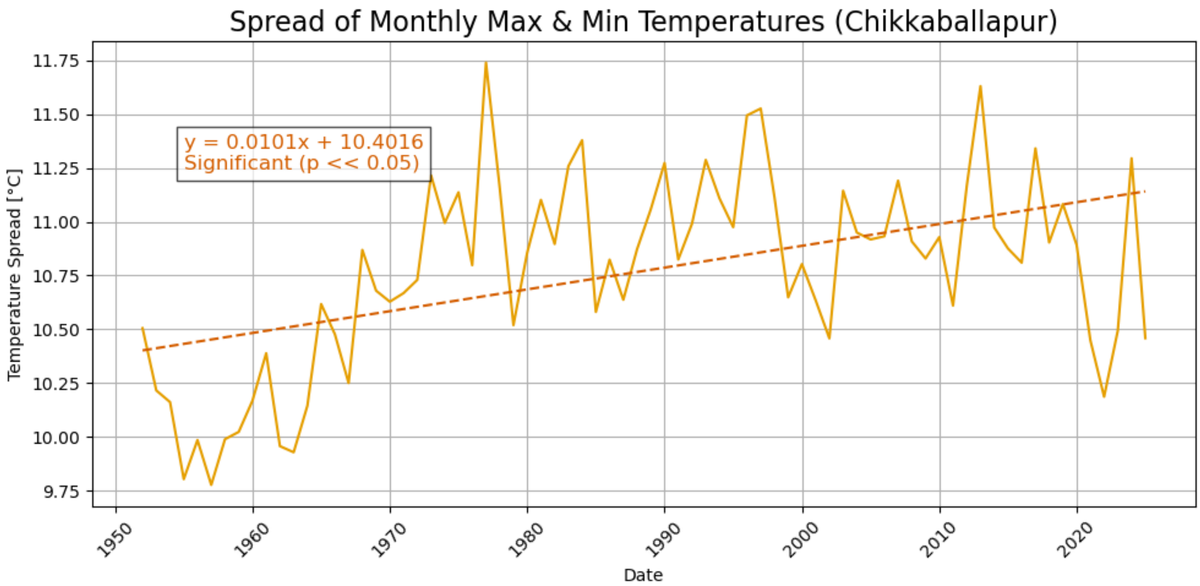


Figure A4. Monthly DTV in Chikkaballapur for the analysed period with a trend line. Monthly DTV is increasing significantly. This is linked, to the faster rate or warming days (Tmax) than nights (Tmin).

Table A1. Summary of the Tmin and Tmax changes in the (2005-2024) and (1951-1971) periods in Raichur and Chikkaballapur

	Difference in (2005-2024) and (1951-1970) temperature values [°C]
Tmin Raichur	-0,1
Tmax Raichur	0,8
Tmin Chikkaballapur	0,2
Tmax Chikkaballapur	0,7

Table A2. Summary statistics of the Tmin and Tmax temperatures in Raichur for years 1951-1971 and 2005-2024.

	Tmin Raichur		Tmax Raichur	
time perioid	(1951-1970)	(2005-2024)	(1951-1970)	(2005-2024)
mean [°C]	21,1	21,0	32,7	33,5
std [°C]	3,1	3,3	3,7	3,7
min [°C]	10,2	9,7	23,1	24,1
1st quartile [°C]	18,9	18,8	29,9	30,8
2nd quartile [°C]	21,7	21,7	31,7	32,5
3rd quartile [°C]	23,0	23,1	35,4	36,1
max [°C]	28,8	28,7	42,5	43,7

Table A3. Summar statistics of the Tmax and Tmin temperatures in Chikkaballapur for years 1951-1971 and 2004-2024.

	Tmin Chikkaballapur		Tmax Chikkaballapur	
time period	(1951-1970)	(2005-2024)	(1951-1970)	(2005-2024)
mean [°C]	19,4	19,6	28,8	29,5
std [°C]	2,4	2,4	1,7	1,6
min [°C]	10,4	10,1	21,4	23,3
1st quartile [°C]	18,0	18,3	27,7	28,5
2nd quartile [°C]	20,0	20,3	28,8	29,6
3rd quartile [°C]	20,9	21,2	29,8	30,6
max [°C]	25,2	25,7	36,3	35,2

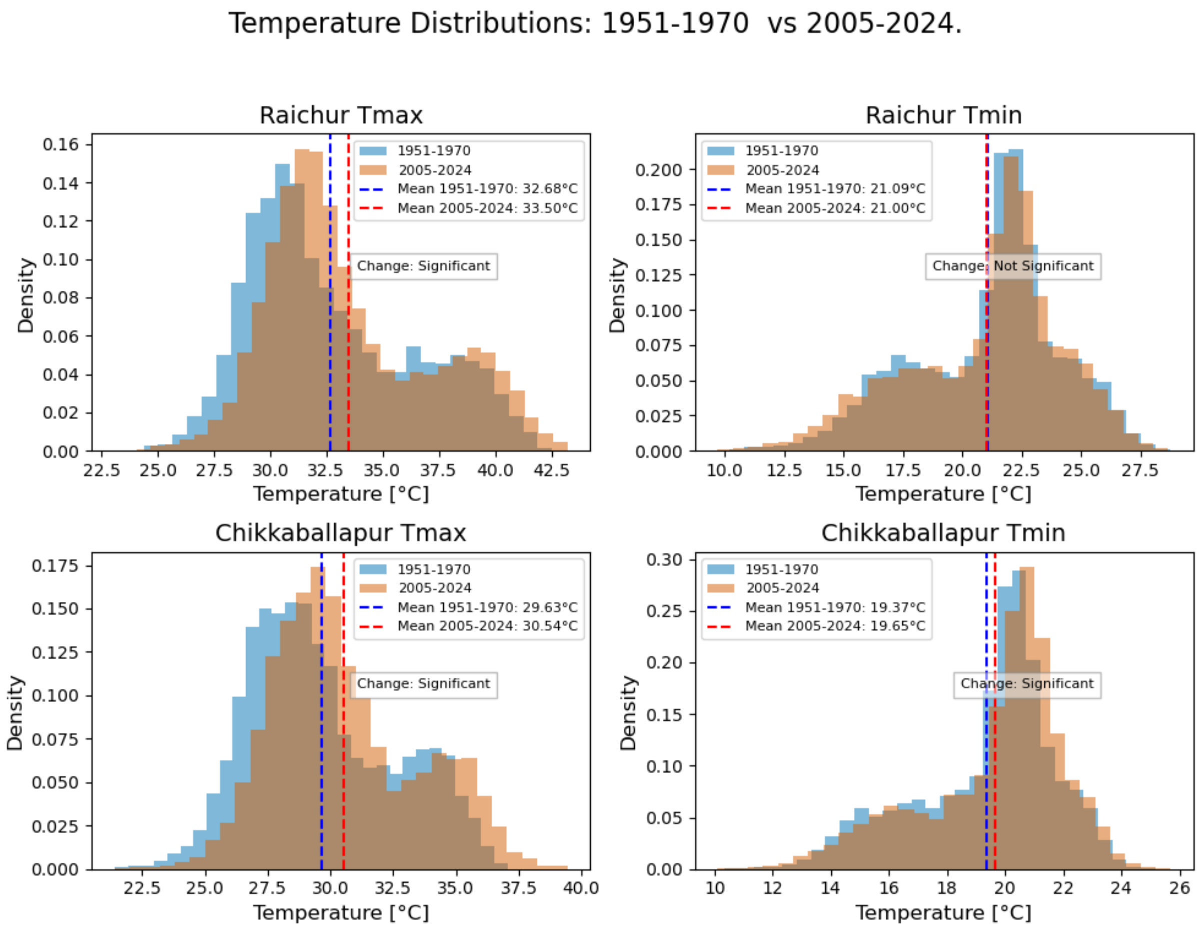


Figure A5. Probability distribution of Tmax and Tmin values for Raichur and Chikkaballapur in the base climate period (1951-1971) (blue) and in the most recent two decades (2004-2024) (orange).

Moving decadal rate of warming

Moving decadal rate of warming was calculated by applying a 10-year moving window to the time series of annual average temperatures (Tavg). Within each 10-year window, a linear regression was performed to fit a straight line to the temperature values. The slope of this line indicates the rate of temperature change per year. To express this as a decadal rate, the slope was multiplied by 10. The resulting warming rate (in °C per decade) was then associated with the midpoint year of each window, producing a time series that illustrates how the rate of warming has evolved over time.

While previous sections in the Appendix A (Fig. A1) established a clear long-term warming trend in both Raichur and Chikkaballapur, a closer analysis using a moving decadal window reveals substantial variability in the rate of warming for average daily temperature (Tavg) over time. In certain decades, the warming trend slows or even temporarily reverses (see Figure A6). This fluctuation indicates that short-term climate variability significantly influences temperature patterns, alongside the underlying long-term warming trend.

The patterns of decadal warming and cooling rates between the two regions are correlated (correlation coefficient of 0.7) indicating that the general temperature dynamics are most likely consistent throughout the region. These variations in decadal warming and cooling rates may reflect broader climatic events, such as the El Niño–Southern Oscillation (ENSO), which is known to influence monsoon and temperature patterns across India (Joshi et al. 2020).

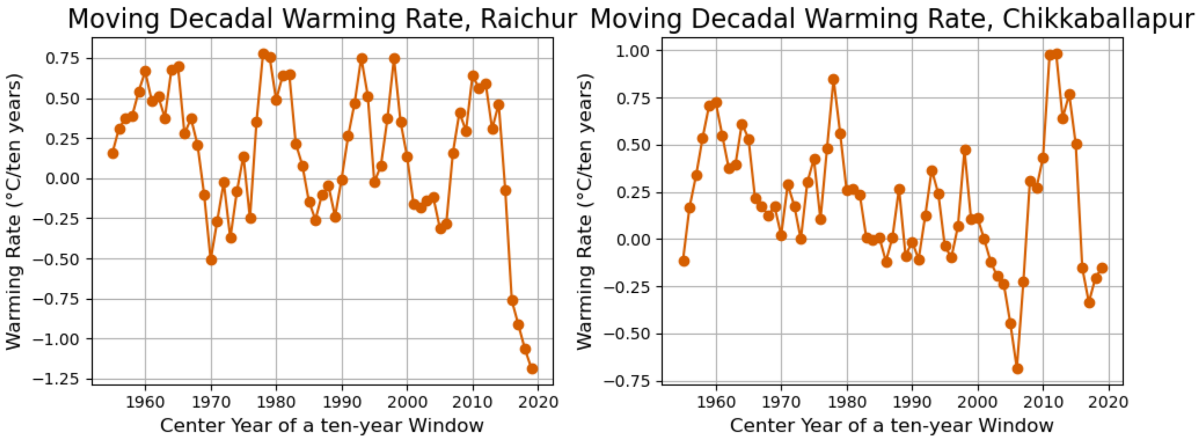


Figure A6. Moving decadal warming rate in Raichur and Chikkaballapur.

This observation supports the idea, discussed by Srinidhi et al. (2024), that relying solely on long-term averages from climate models can obscure the interannual variability that farmers experience. As climate risk is not only about averages but also about extremes and timing. Decadal variability in warming trends reinforces the need for flexible and adaptive agricultural planning.

Temperature anomalies and climate variability

Temperature anomalies were calculated for both Tmin and Tmax, using the full period average (1951–2024) as the baseline. The anomaly represents the difference between the observed temperature on a given day and the long-term average for that same calendar day: This allows for a standardised comparison across years.

Distinct temperature anomaly patterns have been observed in both regions, characterised by clear seasonal and interannual variability. The Figures A7 and A8. presents a heatmap of temperature anomalies for Tmax and Tmin temperatures in both regions.

For Tmax, recent years show a marked increase in hot anomalies, particularly between days 130 and 160 of the year (early May to early June)- a critical growth phase for many crops. Tmin anomalies, on the other hand, display seasonal clustering but show no significant long-term trend. The summer period (days 160–290; May to mid-October) has relatively few Tmin anomalies, whereas the post-monsoon and winter months (days 290–5; mid-October to early January) show a substantial increase in both high and low temperature anomalies (Figures A7 and A8).

These observations point to complex and uneven seasonal temperature change dynamics. They suggest that climate change is altering patterns of thermal stress (particularly for Tmax) in ways that vary by season, a nuance often overlooked when relying on annual averages.

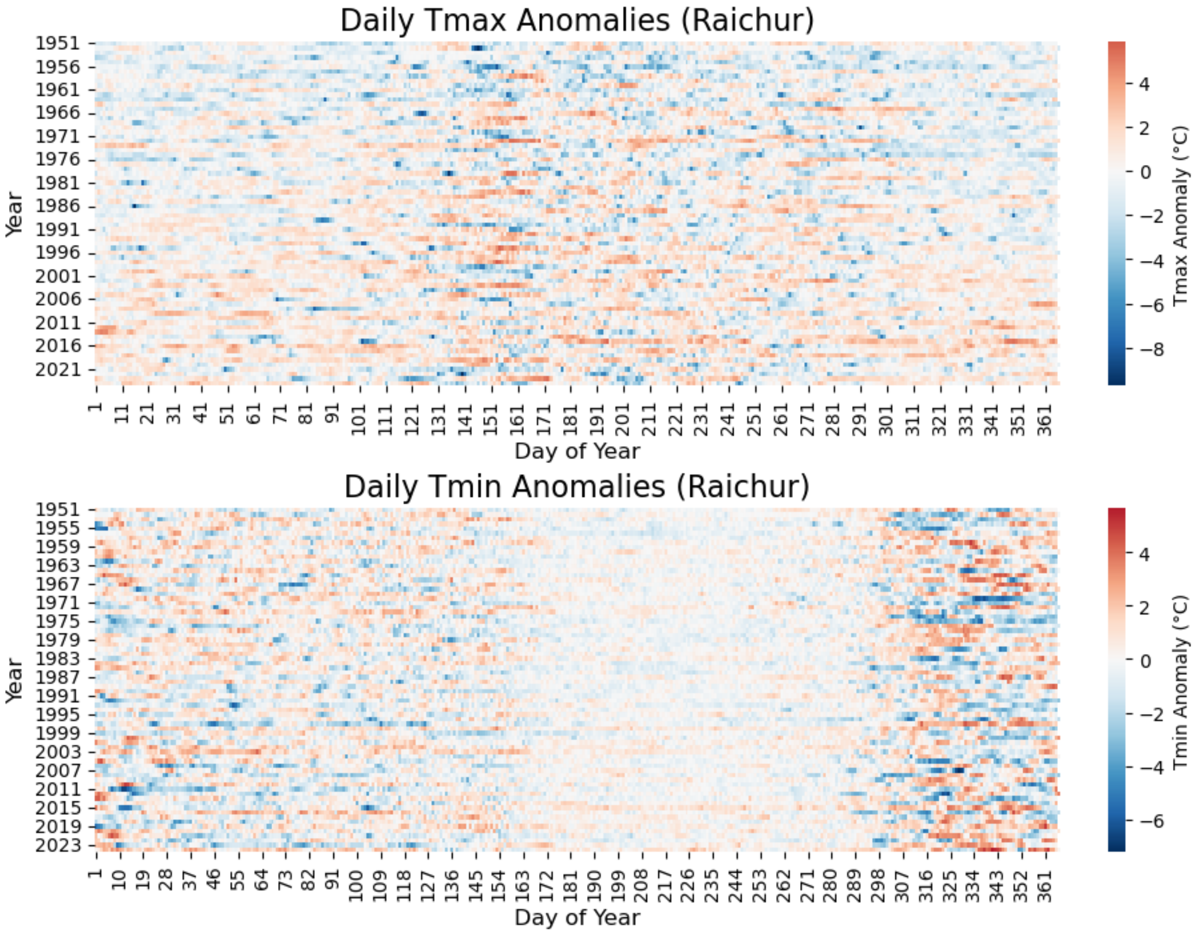


Figure A7. The temperature anomalies for Raichur for every recorded day. For more information on the temperature anomalies see Methodology section.

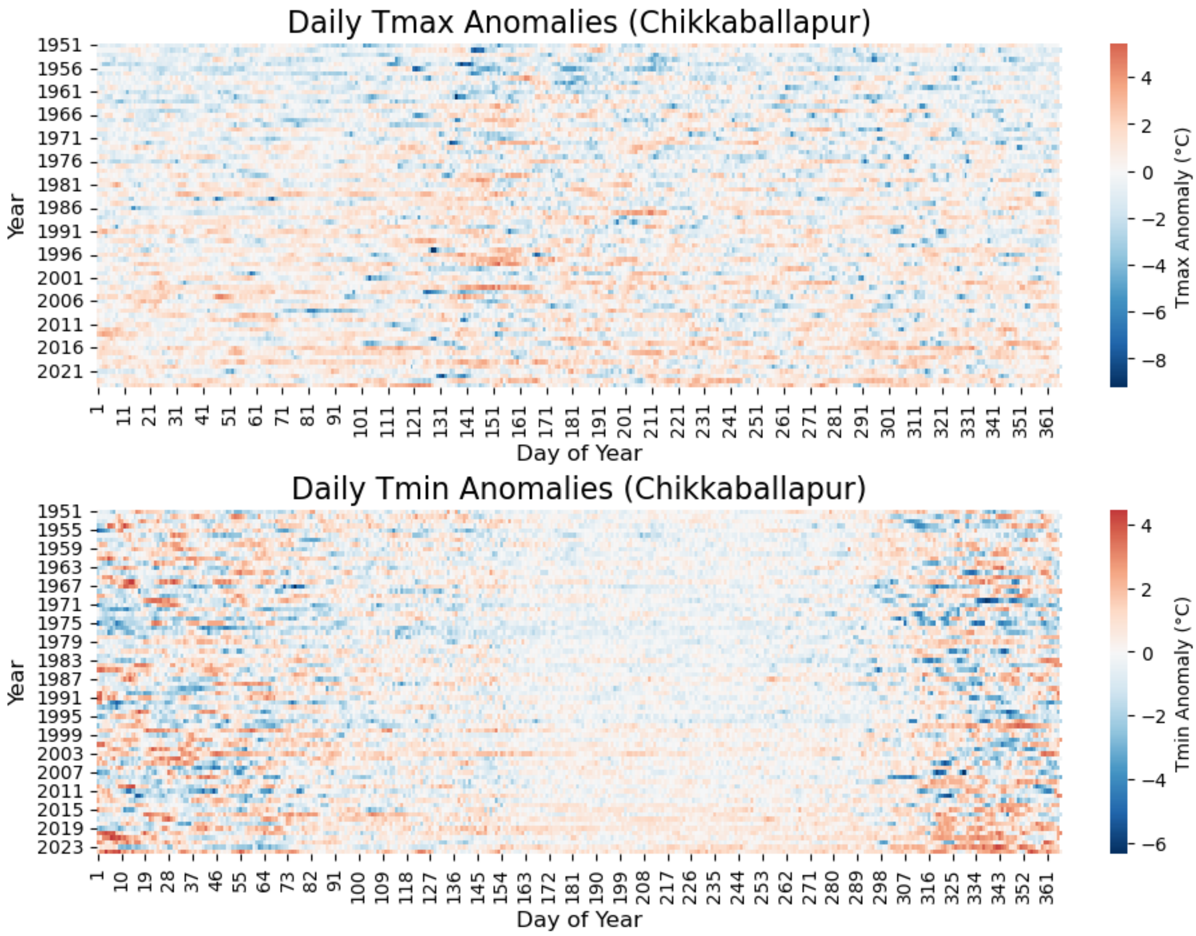


Figure A8. The temperature anomalies for Chikkaballapur for every recorded day. For more information on the temperature anomalies see Methodology section.

Seasonal (Kharif and Rabi season) temperature change

Seasonal changes play a crucial role in agriculture, particularly the distinct temperature patterns between the Kharif (wet, summer) and Rabi (dry, winter) seasons. These seasons form the foundation of the agricultural calendar in Karnataka. Any disruptions in their typical weather patterns can significantly impact farming activities. Notably, rising temperatures during the Rabi season pose a serious threat, as they can adversely affect the growth and yield of Rabi crops.

In both regions, a significant increase in values of maximum (Tmax) and minimum (Tmin) temperatures during the Rabi season was observed ($p \ll 0.05$). Chikkaballapur experienced a greater increase in Rabi temperatures, with a mean rise of 1.05°C in Tmax and 0.2°C in Tmin. In contrast, while Raichur also showed an increase in Tmax (of approximately 1.03°C), Tmin declined in recent years by about -0.23°C. These trends show an overall warming of winter temperatures in Chikkaballapur, aligning with the patterns discussed in previous sections in Appendix A (see Figure. A5). Rising winter temperatures have been identified as a major climate stress factor by Srinidhi et al. (2024), indicating that both Raichur and Chikkaballapur may face a higher risk of adverse impacts on Rabi crops. In Raichur, the contrasting trends long-term changes in Tmax and Tmin point to an increasing diurnal temperature variation (DTV) during Rabi season, which could lead to more extreme and unpredictable weather conditions. Changes in probability distribution of Tmax and Tmin for the Rabi season for both districts is shown in the Figure 5 section 3.1.3 in the main text.

During the Kharif season, both regions exhibited a significant increase in maximum temperatures (Tmax) ($p << 0.05$), with Chikkaballapur experiencing a rise of 0.75°C and Raichur 0.56°C. Minimum temperatures (Tmin) in Chikkaballapur also showed a significant increase of approximately 0.3°C ($p << 0.05$). Tmin in Raichur did not change significantly during the Kharif season ($p = 0.12$) (see Figure A9).

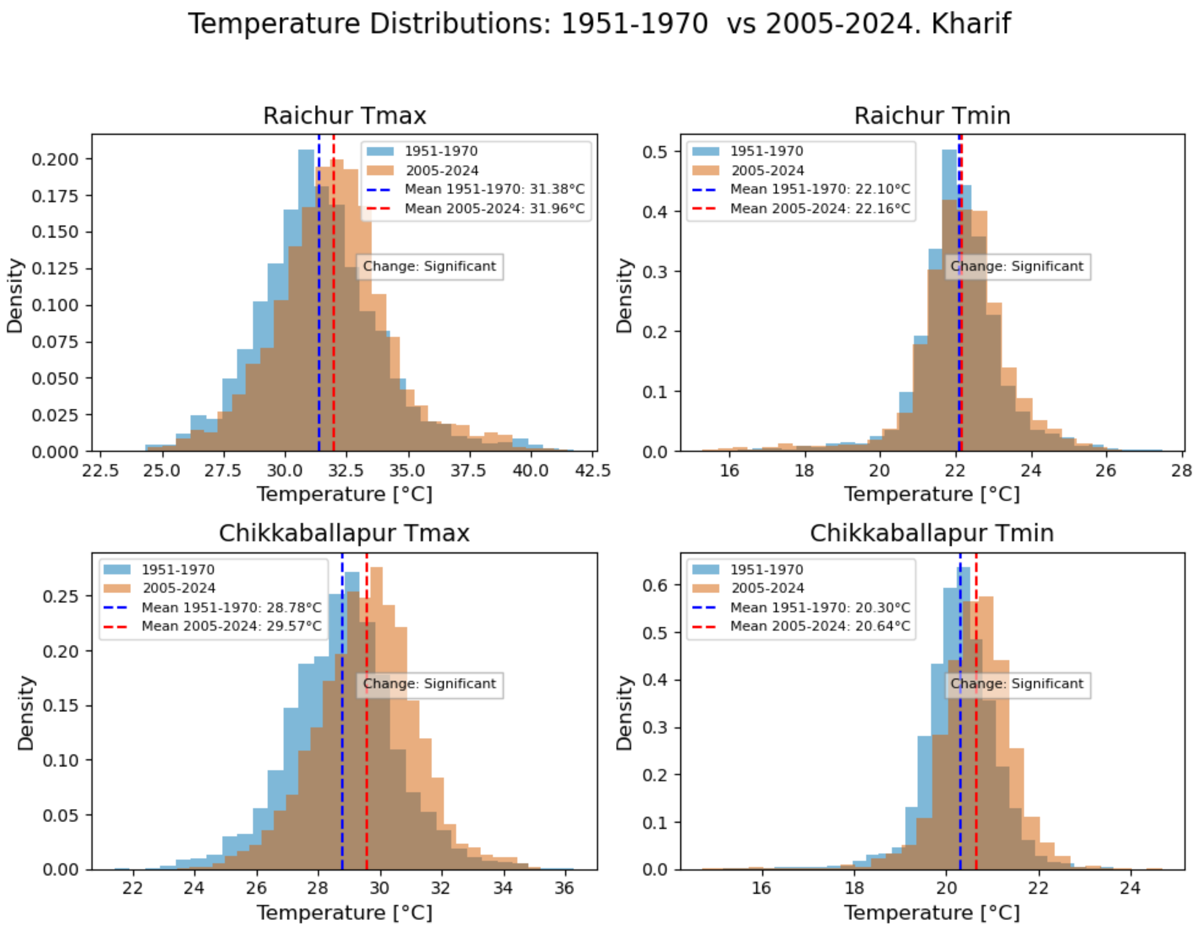


Figure A9. Probability distribution of Tmax and Tmin values in Kharif season in Raichir and Chikaballapur in the time period of 1951-1970 (blue) and 2005-2024 (orange). For Rabi seasons see section 3.1.3 in the main text.

Number of hot and cold days in a year

Cold days are defined as The 3.5th percentile of the lowest daily temperatures (i.e., the coldest 3.5% of days) was used as the threshold for each region. This resulted in a cold day threshold of 15 °C for Raichur and 14 °C for Chikkaballapur. "Cold days" are defined as days with temperatures below these thresholds.

The number of hot days, defined as days with maximum temperature exceeding a certain threshold is a key indicator of climate stress in agriculture . Although the year-to-year variability is high, with a standard deviation of approximately 16 days in Chikkaballapur and 12 days in Raichur, a clear long-term trend of increasing the number of hot days is evident in both regions. On average, Chikkaballapur experiences more hot days per year than Raichur, 27 days vs. 22 days, respectively. The number of hot days in both regions is significantly different ($p < 0.05$). This difference likely reflects microclimatic factors, including elevation and landscape characteristics as well as different threshold value for classification of a hot day.

Chikkaballapur has a faster rate of increasing hot days (+0.38 days/year) compared to Raichur (+0.19 days/year). However, the difference in these rates is not statistically significant ($p > 0.05$), suggesting that while regional variation exists, the overall warming signal is consistent across regions. The change of number of hot days in Chikkaballapur is presented in the Figure. A10, for Raichur see section 3.1.2 in the main text.

In the past two decades, years with only a few, and over 70 hot days were recorded. Due to a very high variance in the number of hot days, it is difficult to state the expected number of hot days in a year now, compared to representative historical climate.

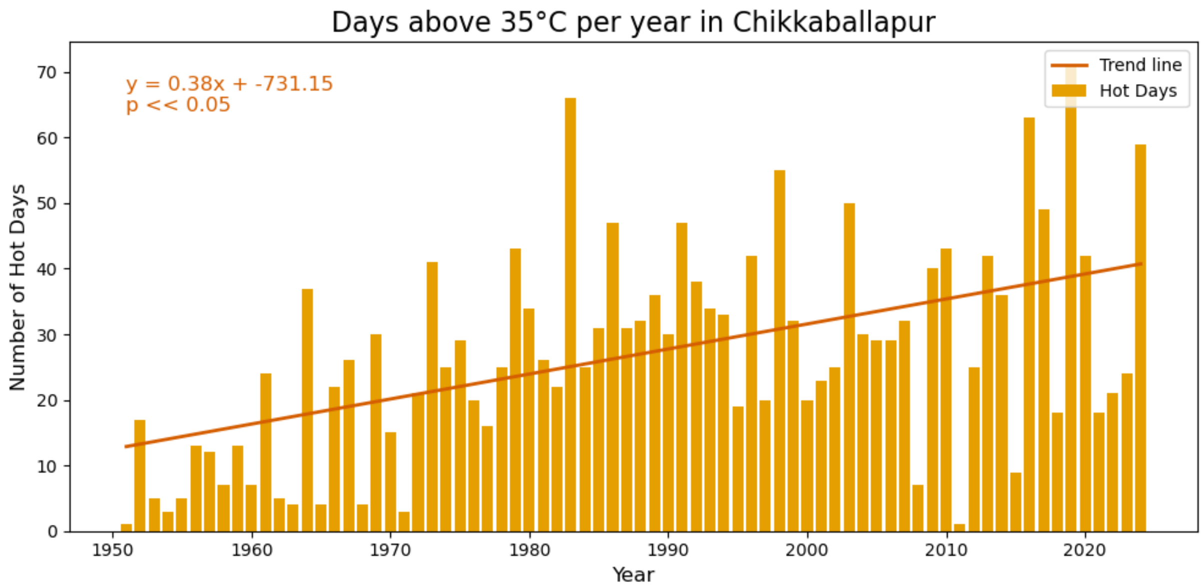


Figure A10. Number of hot days (>35°C) in Raichur with a trend line, slope and the p-value for the significance of the rate of change (red). For the information on the temperature threshold selected see the Methods section. For the number of hot days in Raichur see section 3.1.2 in the main text.

The change in number of cold days over the years seems to be relatively stable, with no statistically significant increases or decreases. High variation (around 10 days) in the number of cold days is present in both regions, with a noticeable clustering of cold days in the early to min 1970's (see Figures A11 and A12).

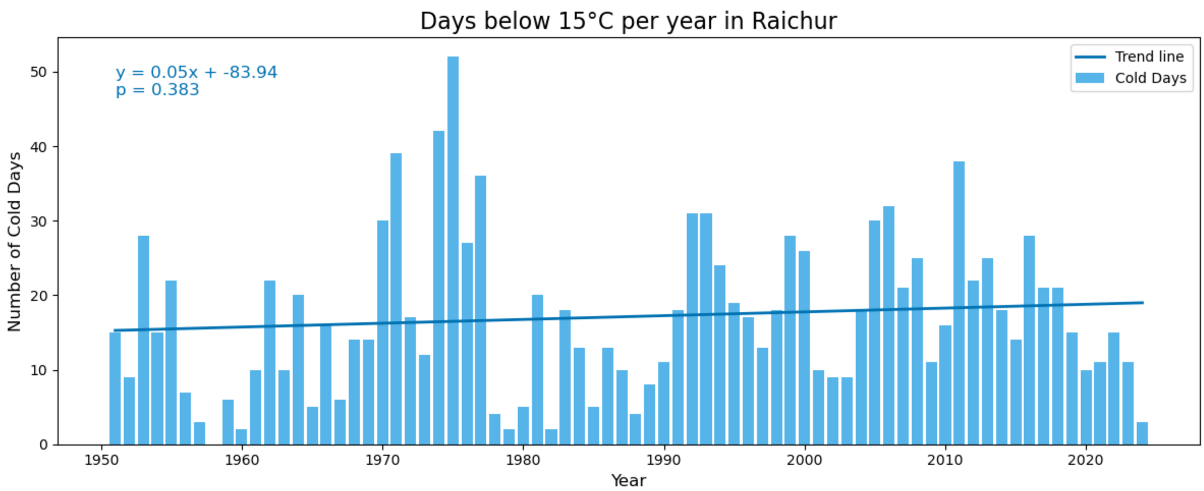


Figure A11. Number of cold days (<15°C) in Raichur with a trend line.

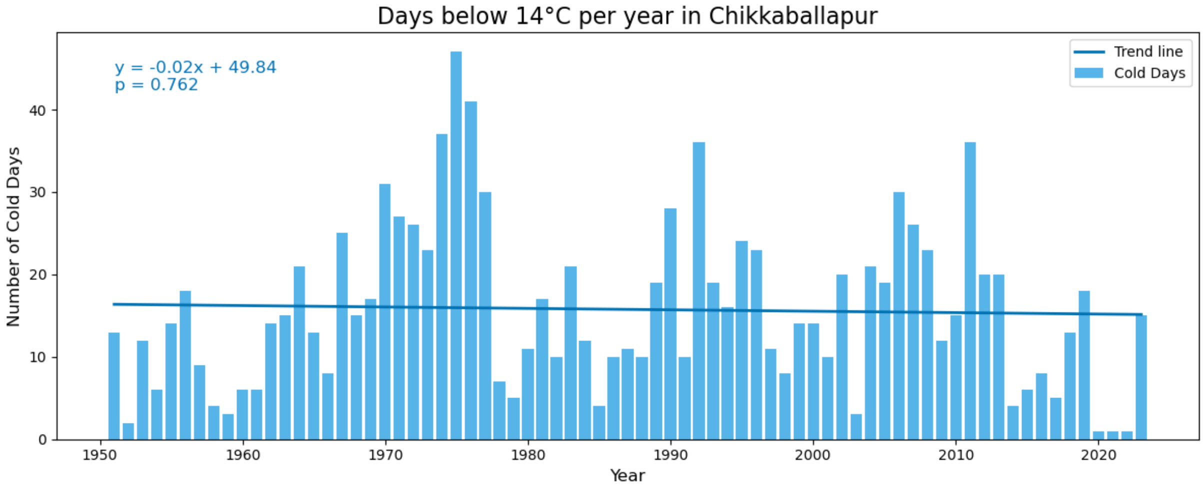


Figure A12. Number of cold days (<15°C) in Chikkaballapur with a trend line.

First and hot days in the year

The first and last occurrences of hot days in both the representative climate and present conditions were analysed. Hot days are now appearing earlier in the year in both regions, while the timing of the last hot day shows a more varied pattern. In Raichur, the last hot day hasn't shifted significantly within the year, extending the hot day window into the spring and potentially affecting agricultural activities like sowing. In contrast, Chikkaballapur's last hot day has shifted about 20 days earlier, indicating that the hot day window is moving earlier without a major change in its duration. For the overview of emergence of the first hot day in Raichur and Chikkaballapur see section 3.1.2 in the main text. For the last hot day in both regions, see Figure A13 below.

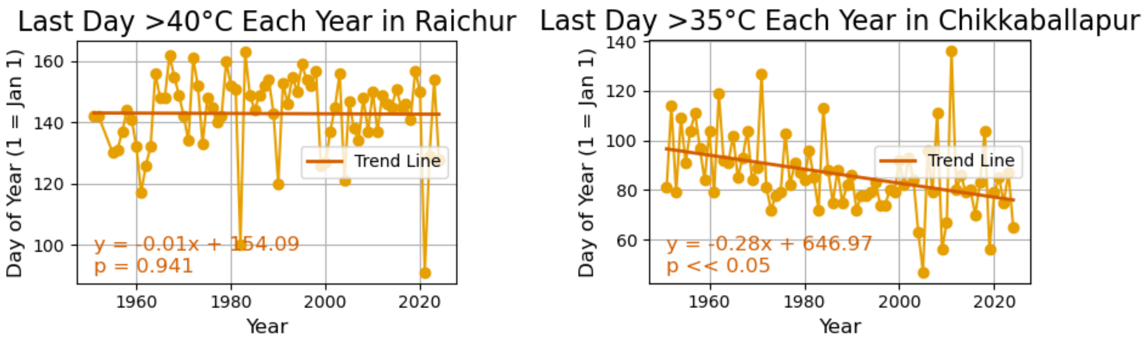


Figure A13. Last hot day in the year in Raichur (right) and Chikkaballapur (left) over the years.

Cold streaks

Occurrence of consecutive cold days, also referred to as cold streaks were analysed for both regions. The analysis included the change of length of the longest cold streak in a year, mean length of a cold streak and the number of cold streaks in a year. For those events, no significant change was observed. This finding coincides with a relatively stable values of Tmin over the years, described in more detail in previous section of Appendix A (see Figure A2) For the overview of the analysed events, see Figures A13 and A14.

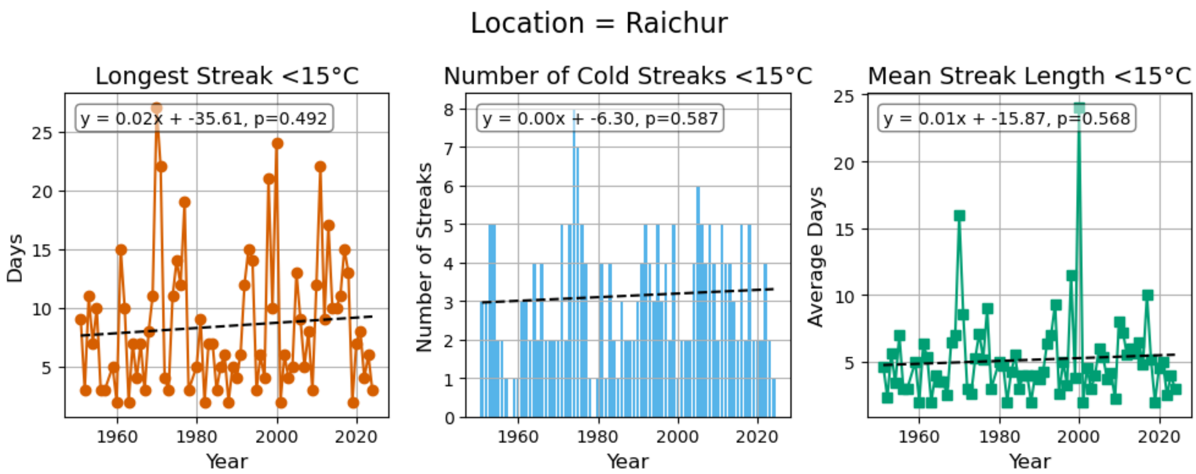


Figure A13. Length of the longest cold streak (orange), number of cold streaks (blue) and mean length of a cold streak (green) over the years in Raichur.

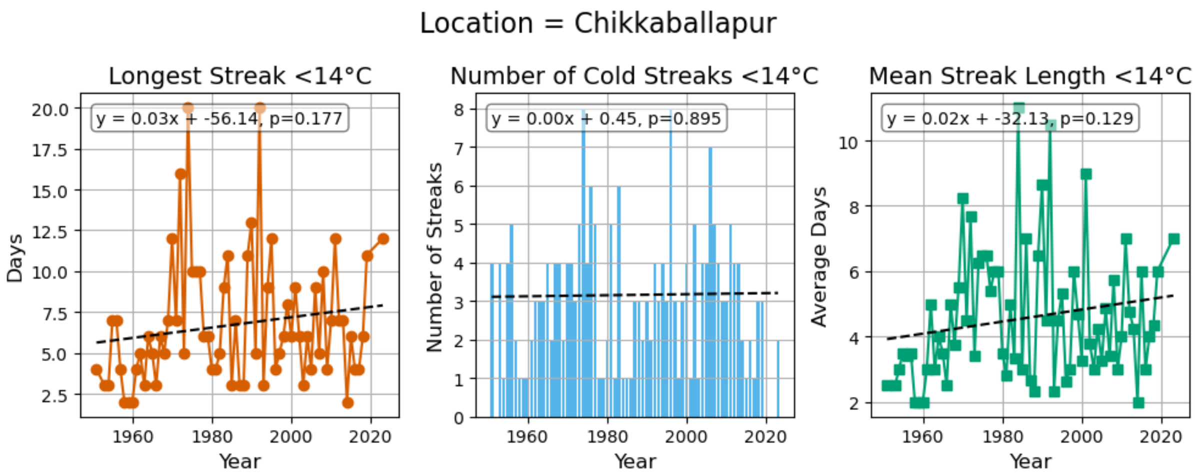


Figure A14. Length of the longest cold streak (orange), number of cold streaks (blue) and mean length of a cold streak (green) over the years in Chikkaballapur.

Appendix B – Additional rainfall data analysis

Total rainfall

Annual average total rainfall and annual monthly total rainfall are calculated by first averaging the amount of precipitation over all the available datapoints for both Raichur and Chikkaballapur. Afterwards these average daily precipitation amounts are summed both on the scale of months and years. Overview of the annual average total rainfall for both regions is presented in the Figure B1 (top panel for Raichur, and bottom one for Chikkaballapur). Overview of the monthly average total rainfall for both regions is presented in the Figure B2 (top panel for Raichur, and bottom one for Chikkaballapur).

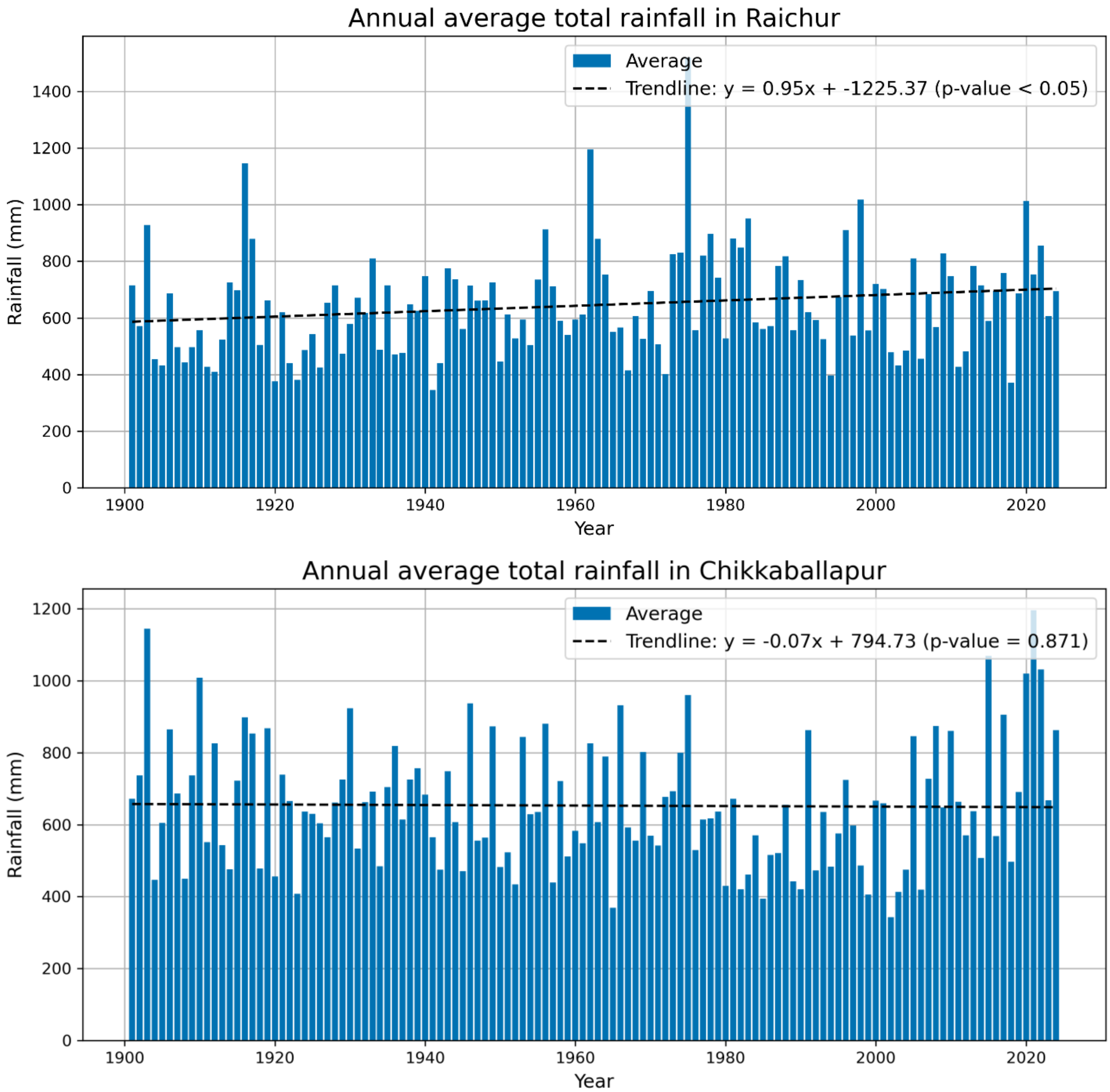
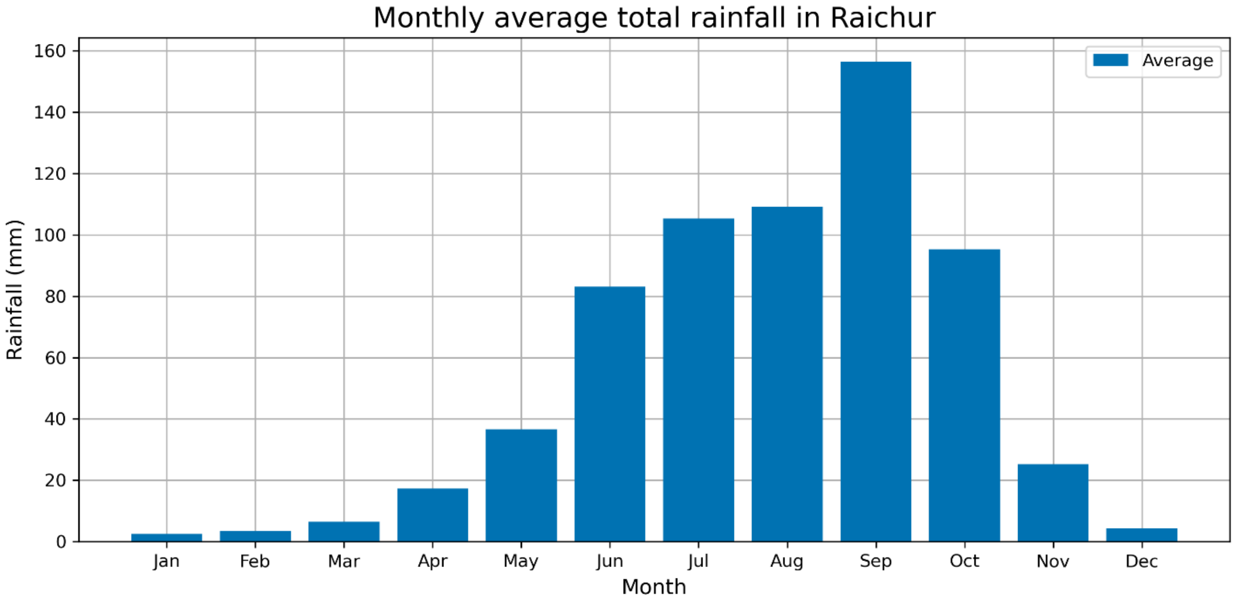


Figure B1. Annual average total rainfall in Raichur (top) and Chikkaballapur (bottom) over the years with a trend line (black).



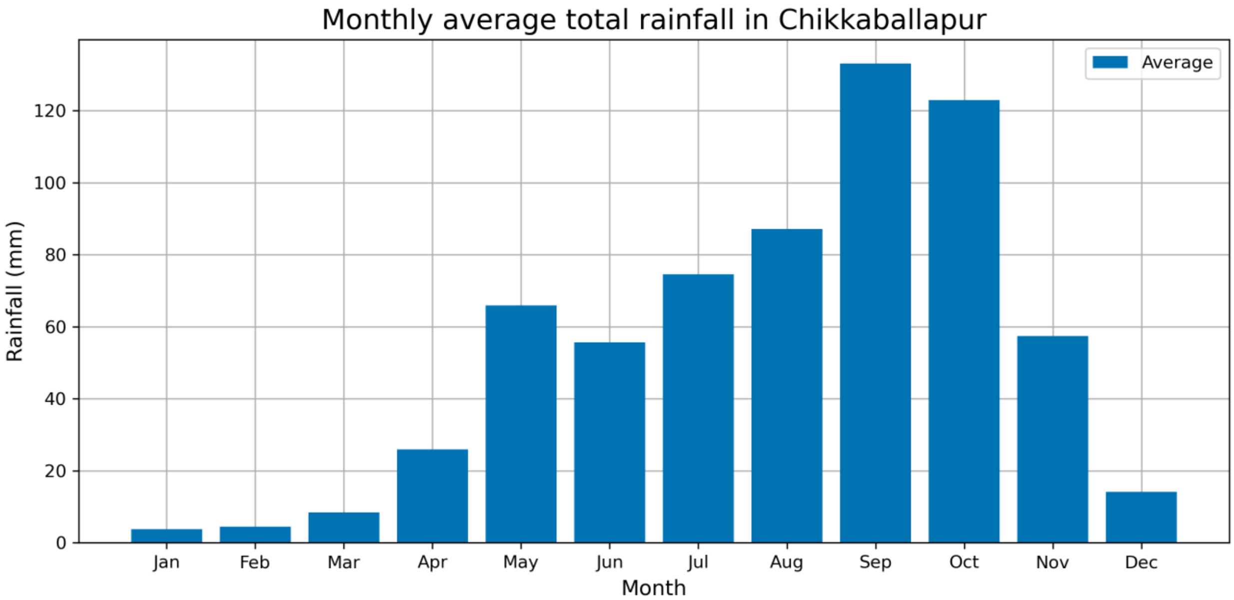
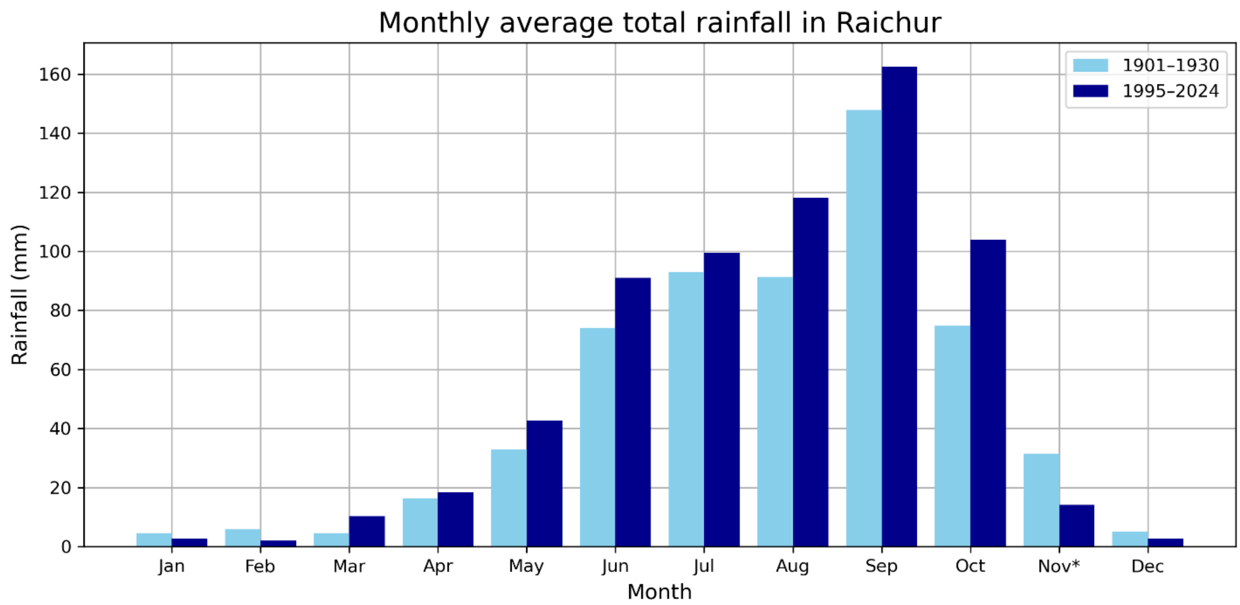


Figure B2. Monthly average total rainfall in Raichur (top) and Chikkaballapur (bottom). Kharif season is characterised by high precipitation in the summer months.



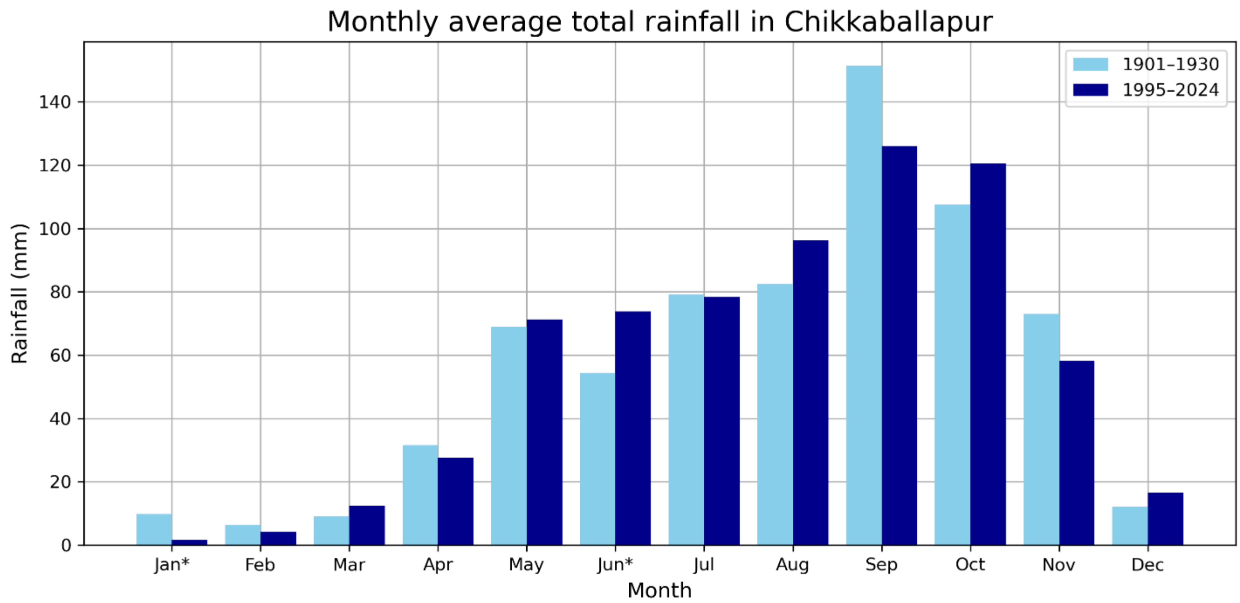


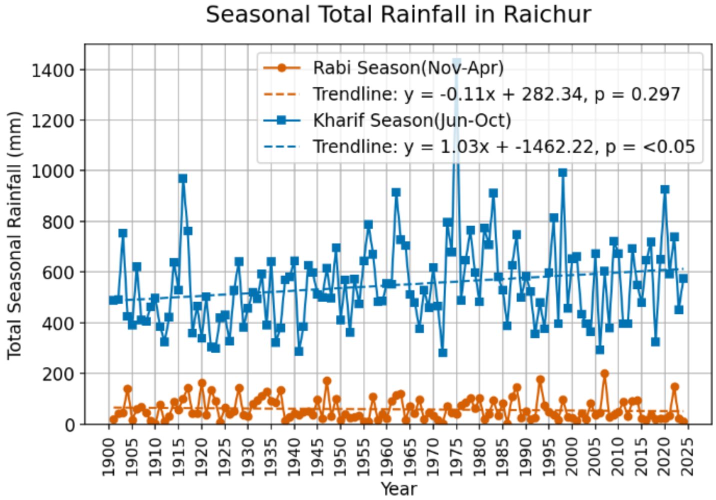
Figure B3. Monthly average total rainfall in Raichur (top) and Chikkaballapur (bottom) in todays' climate (dark blue), and representative climate (pale blue).

Rainfall during Rabi and Kharif season

Rainfall during the Rabi season was distinguished between the two seasons, Rabi and Kharif, the total amount of rainfall has been calculated for each of these seasons per year per region. In Raichur, the Kharif season records higher total rainfall compared to the Rabi season (Figure B4). The rainfall during the Kharif season shows notable variability, including extreme peaks in 1975 and shows a positive linear trend, as indicated by the orange dashed trendline. This trend is statistically significant with a p-value of <0.05, suggesting a consistent increasing trend in rainfall during the Kharif periods. In contrast, the Rabi season showed relatively less fluctuation across the years. The corresponding blue dashed trendline has a p-value of 0.297, indicating that the change in Rabi season rainfall overtime is not statistically significant.

In Chikkaballapur, a similar seasonal pattern is observed, with higher rainfall during the Kharif season than in the Rabi season (Figure B4). However, both seasonal trends are statistically non-significant, meaning no strong evidence of changes of seasonal rainfall over the long periods with p-value 0.697

and 0.343, respectively. Rainfall totals in Chikkaballapur are generally lower than in Raichur for Kharif season.
Even though the trend for the Rabi season are not significant for both regions, they do both hint at a decrease in rainfall.



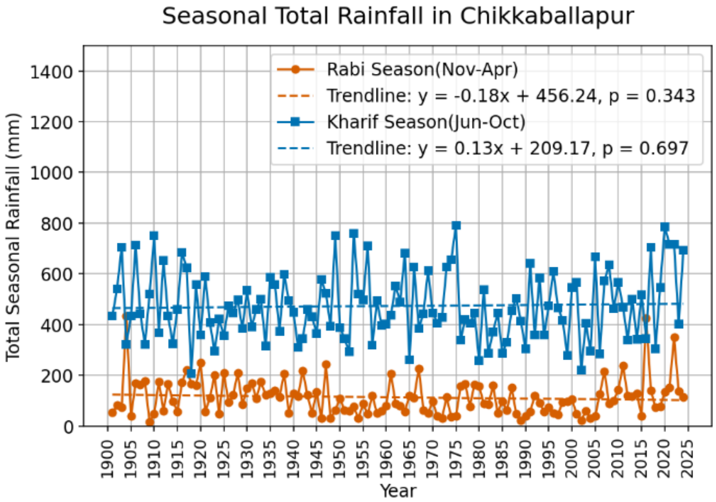
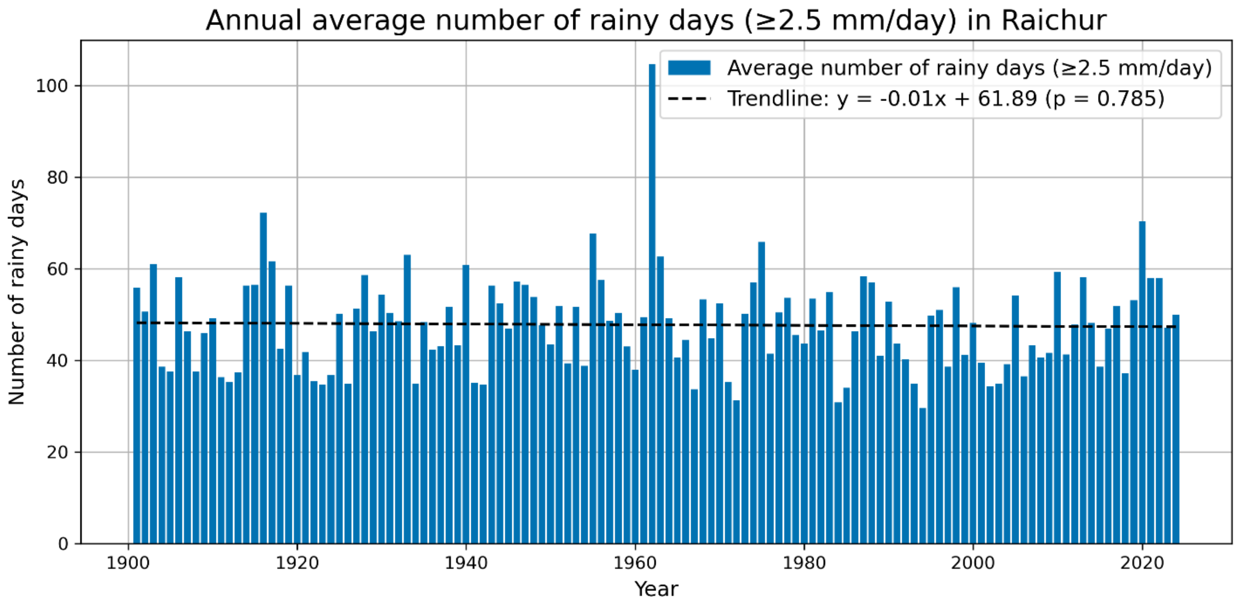


Figure B4. Seasonal total rainfall (Rabi and Kharif season) in Raichur (top) and Chikkaballapur (bottom) between 1901 -2024.

Rainy days

The number of rainy days was calculated based on the threshold of 2.5 mm precipitation per day, all the days that exceeded this threshold were classified as a rainy days. The dataset was averaged over all the points within the region, and filtered to count all the days with rainfall above 2.5 mm. Next, the number of rainy days within a year were summed to calculate the total number of rainy days per year.



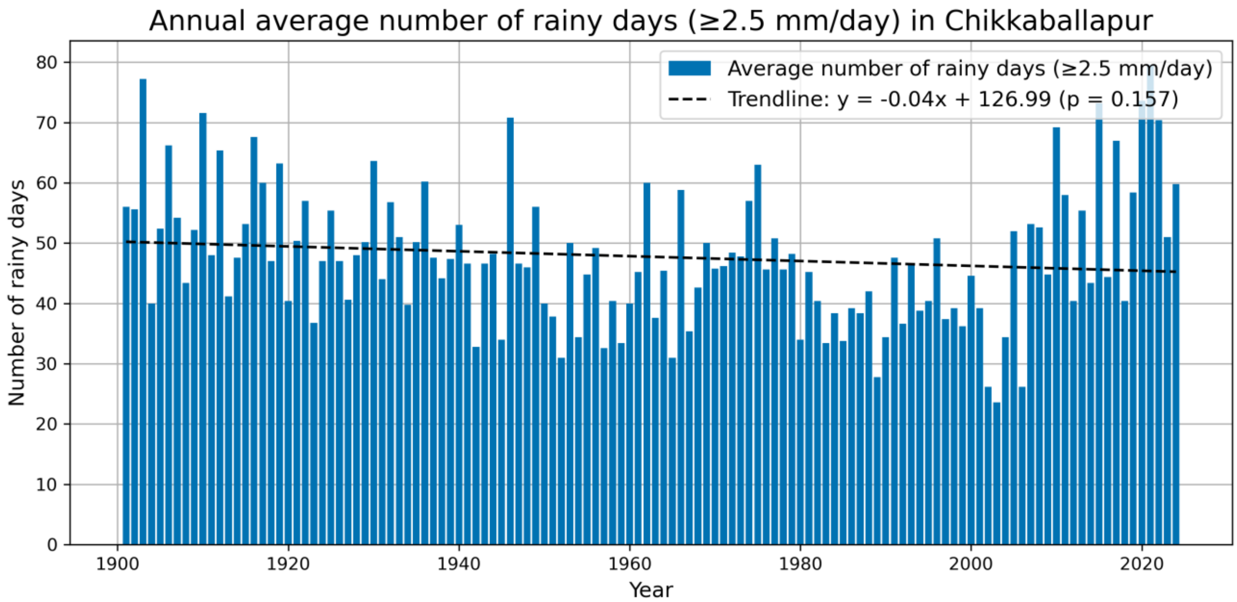
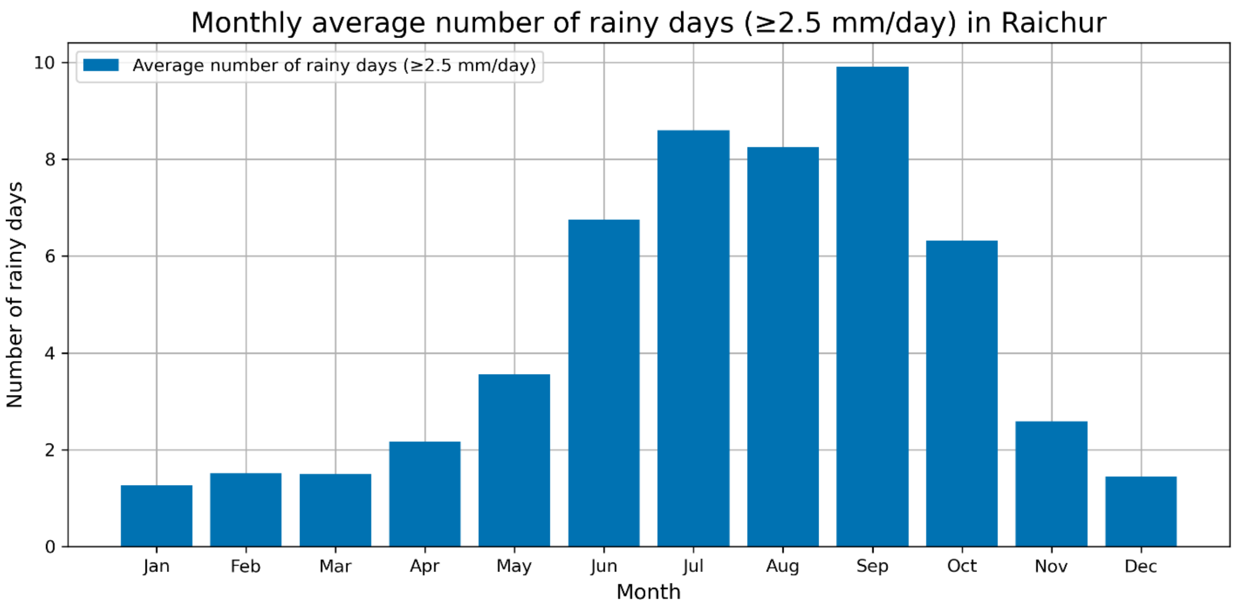


Figure B4. Annual average number of raindy days in Raichur (top) and Chikkaballapur (bottom) with a trend line (black). A day is considered rainy, if 2.5mm or more precipitation was observed.



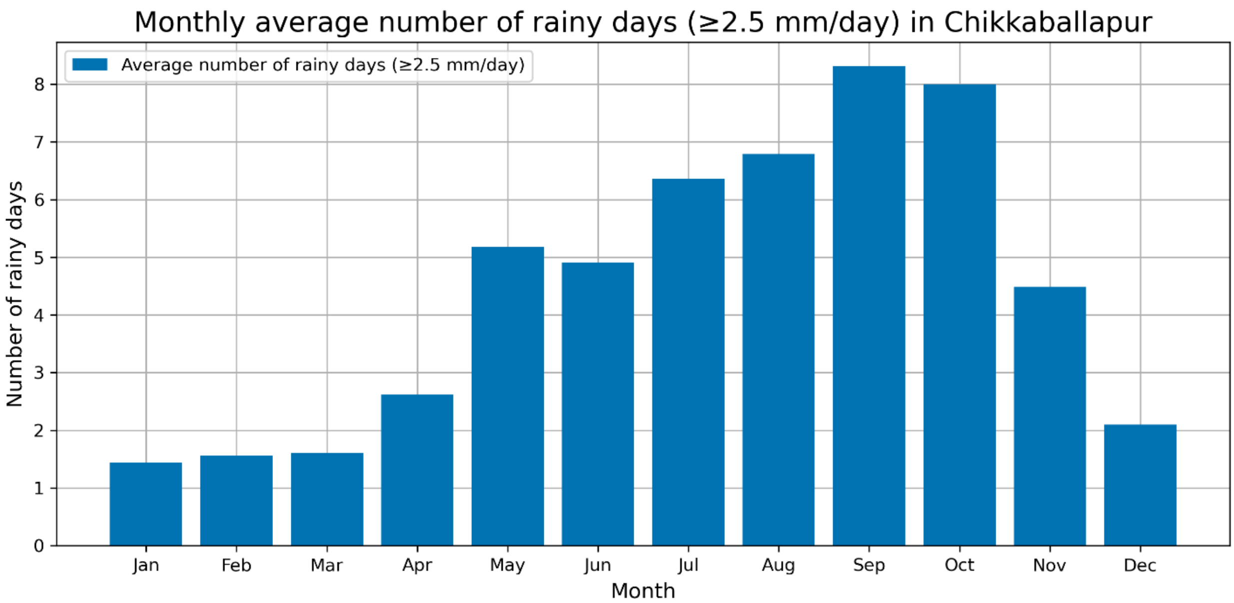
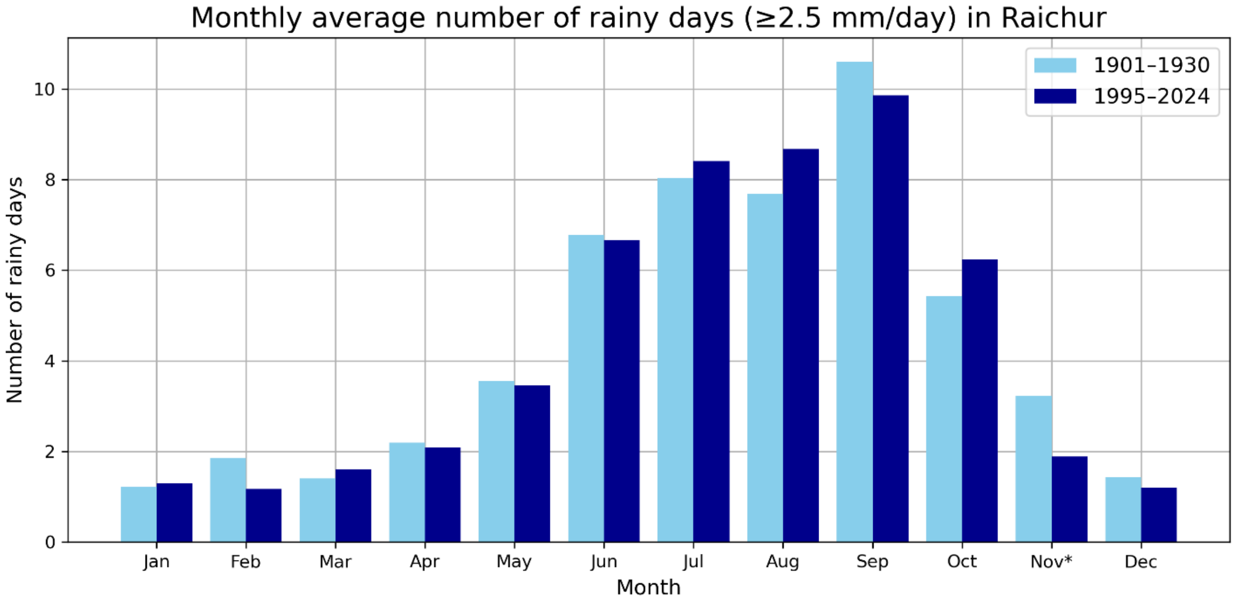


Figure B5. Monthly average number of rainy days in Raichur (top) and Chikkaballapur (bottom). A day is considered rainy, if 2.5mm or more precipitation was observed.



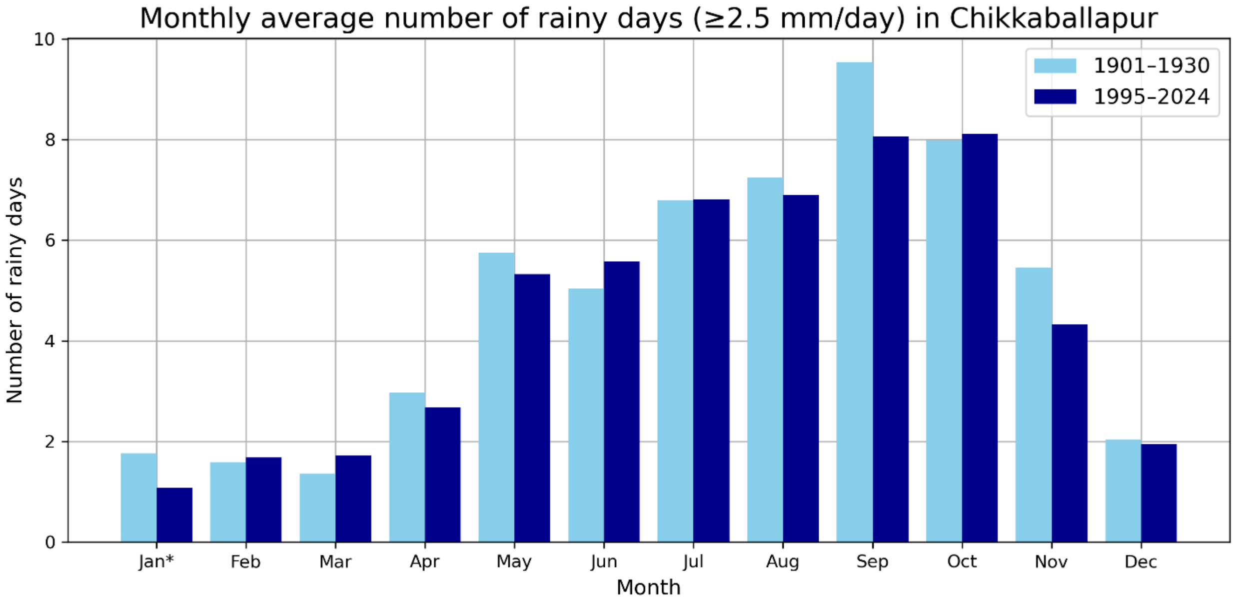


Figure B6. Monthly average number of rainy days now (dark blue), compared to the representative climate (pale blue) in Raichur (top) and Chikkaballapur (bottom). A day is considered rainy, if 2.5mm or more precipitation was observed.

APPENDIX C: SUPPORTING MATERIAL RAINFALL

Dry spells

In Tables C1 and C2 more detailed information can be found on the dry spells and their length, duration and specific timing.

Table C1. Occurrence and length of dry spells in July and August for Raichur.

Year	Length (Days)	Start date	End date
1913	27	19-7-1913	14-8-1913
1918	23	5-7-1918	27-7-1918
1920	35	9-7-1920	12-8-1920
1937	21	21-7-1937	10-8-1937
1939	22	19-7-1939	9-8-1939
1954	21	6-8-1954	26-8-1954
1960	24	28-7-1960	20-8-1960
1964	22	9-8-1964	30-8-1964
1969	21	30-7-1969	19-8-1969
1972	20	2-8-1972	21-8-1972
1973	20	5-7-1973	24-7-1973
1979	21	8-8-1979	28-8-1979
1989	20	25-7-1989	13-8-1989
2000	22	14-7-2000	4-8-2000
2006	22	4-8-2006	25-8-2006
2016	21	3-8-2016	23-8-2016

Table C2. Occurrence and length of dry spells in July and August for Chikkaballapur.

Year	Length (Days)	Start date	End date
1911	21	21-7-1911	10-8-1911
1914	20	4-7-1914	23-7-1914
1915	27	29-7-1915	24-8-1915
1919	24	26-7-1919	18-8-1919
1920	31	16-7-1920	15-8-1920
1928	24	10-7-1928	2-8-1928
1929	21	30-7-1929	19-8-1929

1931	23	4-8-1931	26-8-1931
1934	22	5-7-1934	26-7-1934
1935	21	26-7-1935	15-8-1935
1943	20	10-8-1943	29-8-1943
1944	23	21-7-1944	12-8-1944
1951	31	24-7-1951	23-8-1951
1952	28	24-7-1952	20-8-1952
1958	29	3-7-1958	31-7-1958
1960	23	30-7-1960	21-8-1960
1962	23	7-7-1962	29-7-1962
1964	25	7-8-1964	31-8-1964
1974	20	6-7-1974	25-7-1974
1978	20	18-7-1978	6-8-1978
1979	24	1-8-1979	24-8-1979
1990	26	12-7-1990	6-8-1990
2004	24	14-7-2004	6-8-2004
2006	22	28-7-2006	18-8-2006
2007	21	3-8-2007	23-8-2007
2012	22	23-7-2012	13-8-2012
2016	31	1-8-2016	31-8-2016
2018	31	13-7-2018	12-8-2018

Drought years

In Tables C3 and C4, additional graphs on the drought frequency can be found.

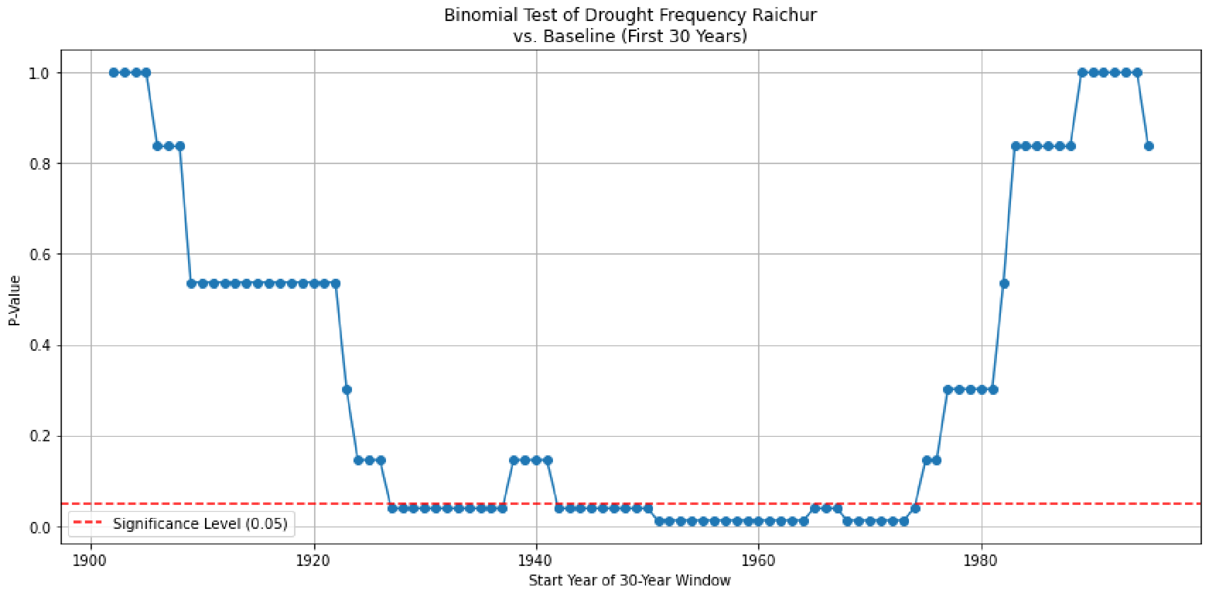


Figure C3: Binomial test of drought frequency of Raichur relative to reference period.

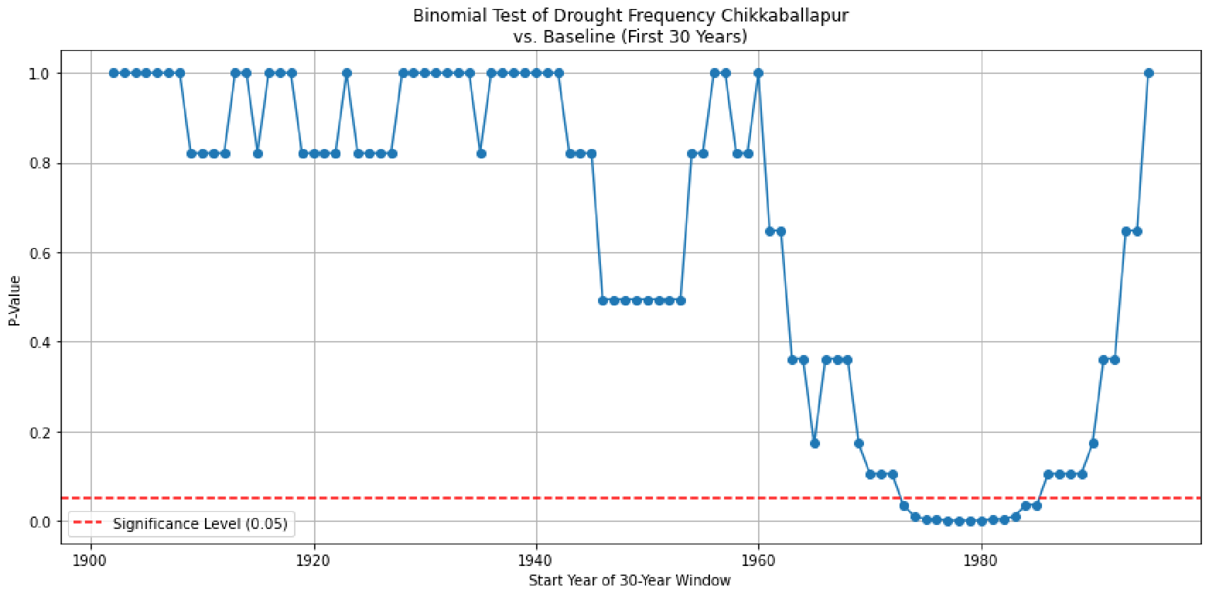


Figure C4: Binomial test of drought frequency of Chikkaballapur relative to reference period.

Appendix D – Supporting material comparative rainfall data

Observational rainfall data

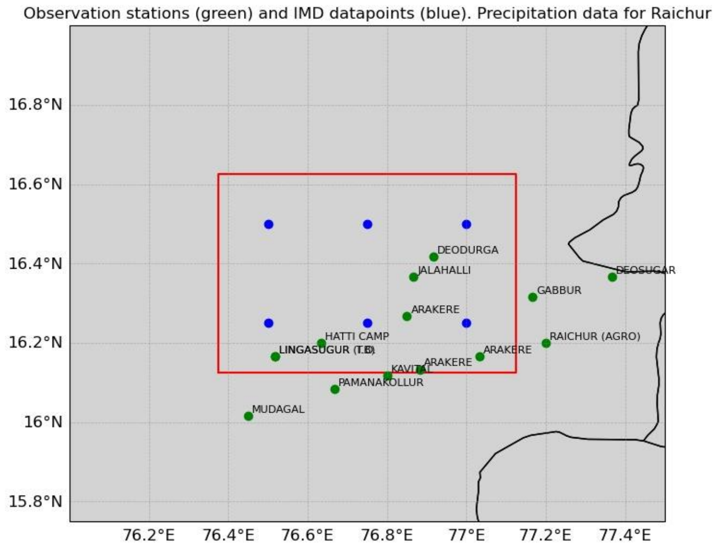


Figure D1. Location of the observation stations in Raichur (green) and centres of IMD grid boxes (blue). Centre of the IMD grid box was assumed to be the location of the modelled rainfall. The red box is the extend of available IMD data, clipped for the shapefile of Raichur. Observed stations were matched to the closest centre of the IMD grid box, to compare the precipitation values.

Table D1. Summary statistics (Correlation, RMSE (%)) of rainfall in Rabi and Kharif season of IMD and IPED rainfall data in Raichur and Chikkaballapur.

5Location	Coordinate		Rabi	Kharif
Raichur	16.5, 76.	Correlation	0.52	0.91
		RMSE	112.96	156.8
		%RMSE	92.71	36.56
	16.5, 77.	Correlation	0.16	0.78
		RMSE	206.44	232.72
		%RMSE	115.27	46.54
Chikkaballapur	13.5, 77.	Correlation	0.31	0.91
		RMSE	159.33	167.54
		%RMSE	80.17	33.15
	13.5, 78.	Correlation	0.42	0.77
		RMSE	158.7	141.32
		%RMSE	74.75	30.59

Table D2. Summary statistics (Correlation, RMSE (%)) of rainfall in Rabi and Kharif season of IMD and observation rainfall data in Raichur.

Location	Data Availability		Rabi	Kharif
Arakere, 16_133_76_8833	2000-2017	Correlation	0.68	0.75
		RMSE	38.81	137.61

		%RMSE	133.55	28.22
Arakere , 16_1667_77_0333	2000-2017	Correlation	0.75	0.71
		RMSE	37.56	165.35
		%RMSE	146.57	31.21
Arakere ,16_2667_76_8500	2000-2017	Correlation	0.67	0.81
		RMSE	28.27	120.85
		%RMSE	74.09	24.13
Deodurga, 16_4167_79_9167	2000-2023	Correlation	0.91	0.78
		RMSE	20.05	166.96
		%RMSE	39.63	30.66
HATTICAMP , 16_2000_76_6333	2000-2017	Correlation	0.66	0.64
		RMSE	39.74	145.19
		%RMSE	93.85	26.95
JALAHALLI, 16_3667_76_8667	2000-2023	Correlation	0.67	0.79
		RMSE	33.84	137.96
		%RMSE	86.72	33.63