# Statistical analysis of extreme temperatures in India in the period 1951–2020

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**Abstract**

Extreme temperatures are directly related to the occurrence of atmospheric extreme events, such as draughts, wildfires, and pollution level increases in urban areas. Policy makers, as well as society, can address such phenomenon by developing and applying methods which estimate and anticipate maximum temperature occurrences. In this research we aim to develop a spatiotemporal model which analyzes maximum temperature trends values in the Indian 543 microregions between 1951 and 2020. In 27% of those, a maximum temperature above **45°**C was observed, at least in a year, with the results of the analysis testifying that 80% of the microregions have an median yearly maximum temperature above **40°**C. Additionally, the results unveiled that East, Southwest and Northwest microregions were the ones where the maximum temperatures had a higher increase with **2°**C being the average. The model developed is based on a Generalized Extreme Value (GEV) methodology, to estimate the maximum temperature values from 20 to 50 years. The projection for 20 years showed that in 16% of those microregions at least one occurrence of a maximum temperature above **45°**C would occur; while in the 50 years one it would happen in 22% of the microregions analyzed.

**Keywords:** Extreme temperatures, Extreme Value Theory, Generalized Extreme Value, India

# 1 Introduction

There is an increasingly number of studies and debates focusing on global warming, trying to unveil its causes and the possible solutions. The rise of the temperatures on Earth, caused by the greenhouse effect (a natural process responsible for the maintenance of globe's heat), is one of its causes, intensified by Human's production of greenhouse gases. Considering this situation, the International Panel for Climate Change (IPCC) stated that the $20^{th}$ century was the hottest, with temperatures rising 0.7°C on planet Earth, and predicting its continuous growth throughout the $21^{st}$ century, if large scale actions to contain this event aren't adopted.

Temperature increases has catastrophic consequences, among which, the increase of the living costs, the effects on the economy, the extinction of plant and animal species and, above all, the risks on human health. Those effects have been studied for different parts of the globe, like Africa [1] and the Middle East and North Africa [2]. Nevertheless, according to [3] one of the main geographical areas to feel the impacts of climate change is southern Asia, mainly India, since "the country is depleting natural resources, thus destroying its environment, mainly due to urbanization, industrialization and economic growth". To prevent depleting natural resources, India is going through a negative socioeconomic and environmental change. "Water and air quality worsen day by day due to the increase of various pollutants in the atmosphere. Moreover, the sectors subject to the greatest exposure to climate change are the country's coastal ecosystems, biodiversity and agricultural productivity".

According to the Joint Research Institute on Global Change, in 2009, India had lots of water resources to be used in sanitation, agriculture, cooking and for drinking. Nevertheless, from one year to the other, India decreases 34% of its available water, making over-exploitation a concern since it might also be affected by climate change. Additionality, the increase on the temperature and its bigger variability within the seasons can lead to a faster melt of Himalayas' glaciers, having as its consequence floods when the glacial lakes surpass their natural limits. In the future, these changes may include less water resources, impacting in the agriculture, urban water supply, and hydropower[1].

Taking into consideration the context presented, students from all parts of the globe have been looking for and developing methods to predict the significant increases in temperature and the places where that phenomenon is more likely to take place. Among the methods researched, The Community Earth System Model low-warming simulations was used to analyze temperature increase in Africa [1], and the Regional Climate Model ALADIN-Climate to predict it for the Middle East and North African countries [2]. Nevertheless, Extreme Value Theory (EVT) stressed out due to being able to space-time model and predict extreme events, allowing to identify in which regions extreme temperatures may occur and to predict it, so public policies and solutions can be applied.

In fact, EVT is a powerful branch of Statics and Probability which focus on distribution tails (upper or lower), enabling to quantify events considered extreme or rare through the analysis of minimum or maximum sample groups. It has been studied and used for a long time, applied to different research areas for observing infrequent events – from management risks [4] to performance analysis in emerging markets [5], as well as to analyze the changes in the temperature in Argentina [6].

In this study we aim to apply EVT to model extreme temperature occurrences in the 543 geopolitical Indian microregions, to analyze and identify which of them are more susceptible to this event, as well as to generate different levels of return. We used the data from the India Meteorological Department (IMD) for the Indian subcontinent, and gridded daily maximum temperature data at 1 degree resolution. We can consider the data used unique, since it provides continuous daily information on the maximum and minimum temperatures from 1951 to 2020, with equal spatial intervals, taken from conventional and remote sensing platforms. This data has been authenticated by several researchers who analyzed and evaluated India's temperature extremes ([7]; [8]; [9]; [10]; [11]; [12]; [13]; [14]; [15]). In fact, high temperatures, droughts, and floods are dangerous events which can occur frequently due to climatic changes. Research on climate change and, more specifically, about the changes on high temperatures are significant ways to manage the environmental resources on a

[1]The impacts on agriculture are already occurring and are one of Indian's government main concern. It is noticed that many farmers are committing suicide, since the droughts destroy their harvests, not being able to pay their loans and having no return on the investments made.

sustainable way. Thus, it is important to have a complete knowledge on temperature's pattern on a changing environment, helping decision making and the communities to adapt to extreme climate events.

This paper is divided in five sections (with the first being the introduction and the fifth the conclusion). Section two discusses the EVT, the asymptotic distributions of minimum and maximum and the generalized distribution of extreme values. Section three aims to describe this study's methodology – the statistics used, thematic maps construction, prediction of the Generalized Extreme Value (GEV) parameters through the maximum likelihood method, test for quality of fit and return levels. Section four presents the main results.

# 2 Methodology

As stated previously, EVT is applied to model minimum and/or maximum data of observable variables, focusing on the tail of the distribution (as other statistical modeling method) and, thus, being a powerful tool to estimate events that rarely occur or which have not occurred yet, from different scientific domains - from financial crises to natural disasters (tsunamis, meteor impacts, earthquakes, among others). In this sense, we consider that EVT was developed with the to goal to create a predictive model to quantify those events, to enable us to reduce and prevent its consequences. That justifies why there are several publications regarding it, in different areas: to analyze long and short-term strategies in the Brazilian market [16] or to study selling stocks in emerging markets [5] in Economy; or even to predict maximum temperatures in Colombia [17]. Despite these studies being relatively recent, and according to [18], the interest in developing extreme event predictive models go back to the $17^{th}$ century, being related to astronomy studies. [19] exposed the first fundamentals in 1928, introducing three possible types of asymptotic distributions of extreme values, known as Gumbel, Fréchet and Weibull distributions. Although those first steps, it was [18] who published the first study that formalizes the statistical application of these distributions, with his methodology being often applied. We also must consider [20] contribution, for showing the necessary and sufficient conditions for the existence of asymptotic distributions of extreme values.

## 2.1 Main limit results

Consider a sample $(X_1, X_2, ..., X_n)$ of independent and identically distributed (iid) arbitrary variables from a main population which distribution function (df) F is unknown.

Considering that $M_n = max_{1\leq i\leq n}(X_i)$ is the maximum of the sample, and assuming that there are normalizing constants $R$ and $a_n(>0), b_n, \epsilon$ and that there is non-degenerate G, such that, for all $X$,

$$\lim_{n\to+\infty} P\left(\frac{M_n - b_n}{a_n} \leq x\right) = G(x).$$

If we choose the proper normalizing constants, G is considered the Generalized Extreme Value (GEV) distribution,

$$G(x) \equiv G(x|\xi) := \begin{cases} \exp\{-[1+\xi x]_+^{-1/\xi}\}, & \text{if } \xi \neq 0 \\ \exp\{-\exp\{-x\}\}, & \text{if } \xi = 0 \end{cases}, \tag{1}$$

with the von Mises-Jenkinson ([16]; [21]) form represented by $a_+ = max(0, a)$. By introducing the shape parameter $\xi$: Weibull ($\xi < 0$), Gumbel ($\xi = 0$) and Fréchet ($\xi > 0$) the GEV model enables to unify the three possible limit max-stable distributions. The shape parameter $\xi$ is linked to the weight of the right-tail and frequently denominated extreme value index (EVI). We can also introduce two more parameters, $\lambda$ related to location, and $\delta$ related to scale. Considering our case study and the unknown character of the normalizing constants $a_n > 0$ and $b_n \in R$, we integrate them in the GEV distribution related to location and scale parameters ($\lambda$ and $\delta$), taking us to the model

$$G(x|\xi, \lambda, \delta) := \begin{cases} \exp\{-[1+\xi\left(\frac{x-\lambda}{\delta}\right)]_+^{-1/\xi}\}, & \text{if } \xi \neq 0 \\ \exp\{-\exp\{-\frac{x-\lambda}{\delta}\}\}, & \text{if } \xi = 0 \end{cases} \tag{2}$$

The Maximum Likelihood or the Probability Weighted Moment methods are frequently used to estimate the parameters ($\xi$; $\lambda$; $\delta$). A Histogram, a Quantile Plot, a Return Level Plot, or a Probability Plot can be used to check the model, with block maxima, the largest observations and the peaks-over-threshold being the most important methods used by the Statistics of Univariate Extremes domain area [21][2].

# 3 Data and methods

India is geographically located between latitude 8.4 and 37.6 N and longitude 68.7 and 97.25°E. Considering its climatic characteristics, the distribution and occurrence pattern of temperature, for regions – North-West India (NW India), North-East India (NE India), Central India and Peninsular India (Figure 1).

To pursue this study, we used the maximum annual temperatures observed in 702 sites in India, between 1951 and 2020. The goal is to identify the microregions which are considered susceptible to extreme temperatures, to recognize the authorities responsible for those places.

To stablish the sites, we considered the smaller areas of India's political microregions. That enables us to reduce the generality of the temperatures. In fact, if we considered even larger regions, it wouldn't be possible to identify the approximate or the exact location of the extreme temperatures. This option also allows an improvement on the effectiveness of preventive measures to be studied and applied, and an easier identification of the political leaders responsible for those sites.

To interpolate those places, interpolation by the nearest neighbors up to 0.5° latitude and longitude was used, a deterministic interpolation that shows the nearest or the geometrically most convenient points in all directions. The

[2]For an EVT overview and related topics see Coles, 2001.

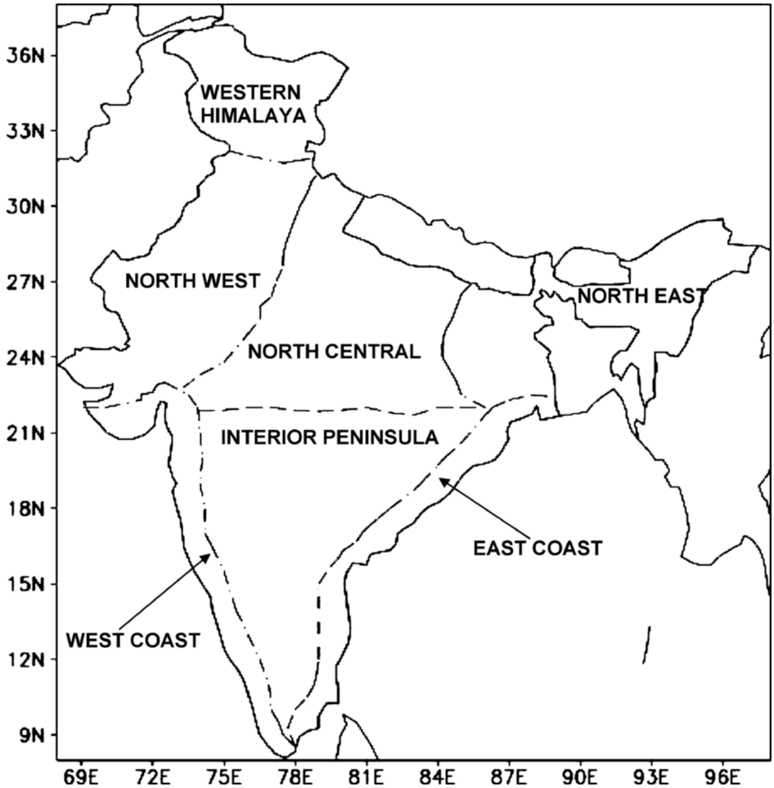



**Fig. 1**: Climatic regions of India: North-West India, North-East India, Central India and Peninsular India

0.5° distance was selected due to the fact of being half the distance from one site to the other, not allowing the algorithm to choose two sites in the same direction and applying the mean of the temperatures registered in those places. This interpolation method was used because it is easy and fast, justifying being frequently applied in sampled studies. According to [22] there is a higher performance of the algorithm nearest neighbors when compared to conventional interpolating algorithms since the interpolation creates time series for microregions. For the microregions that for some year did not result in any value after the interpolation, another nearest neighbors interpolation was performed considering the average of the temperatures of the neighboring microregions of the border.

To build a suitable database, series that had less than 30 years of data were excluded, resulting in the exclusion of the microregion Andaman & Nicobar.

To analyze the data thematic maps of descriptive statistics (minimum, median and maximum), boxplot, and histograms were developed. Considering maps' construction, we used DataMeet[3] for India's shape, the States and Union

[3]http://projects.datameet.org/maps/, Community created maps of India, 2021

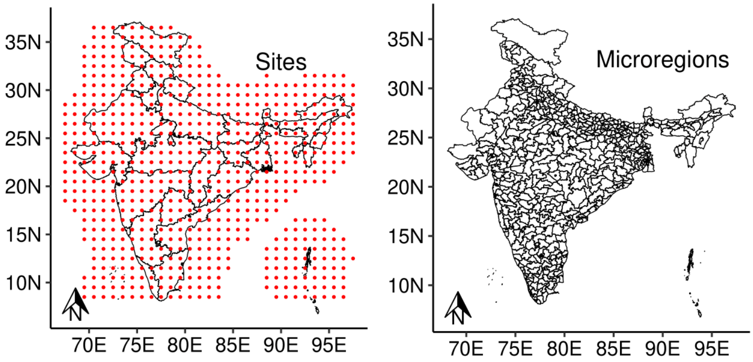



**Fig. 2**: Political Division of India's microregions

Territories boundaries of India, considered from ECI Polling Station Locations Website[4], it can be divided in 28 States and 7 Union Territories. rgdal ([23], 1.5-12) packages for the shape reading and the ggplot2 ([24], 3.3.2) for the map plotting. Figure 2 shows India's geo-political microregions divisions.

The EVT modeling used annual data of maximum temperature in the different Indian microregions. The methodology adopted enabled to develop thematic maps identifying the microregions susceptible to higher temperatures and their return levels. To develop this analysis, we used R version 4.0.2. [25], a language and environment for statistical computing.

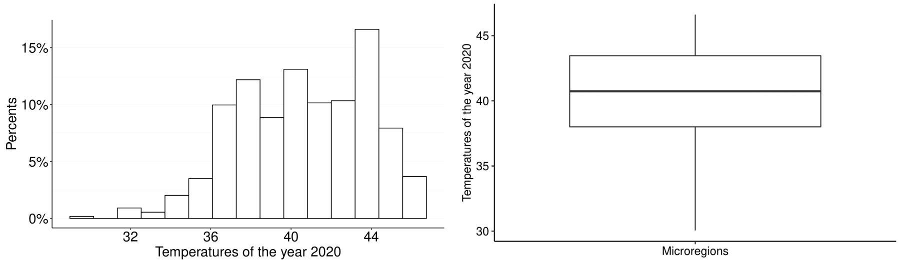
# 4 Results

India integrates 543 microregions. In the last year of this study, 2020, about 58% of them registered, at least for one day of the year, a temperature above 40°C, and 6% registered an even higher temperature, above 45°C. Figures 3 shows the histogram and the boxplot of the maximum temperatures in 2020.

Figure 4 shows the maximum temperatures in 2020 according to the microregions. A large part of India, mainly central India, faced maximum temperatures above 43°C between 1951 and 2020. Oppositely, the lowest annual temperatures, not exceeding 35°C, were registered in Eastern and Southwestern regions.

In the chronological period mentioned, the highest increase in the temperature was registered in East, Southwest, and Northwest regions, as we can see in Figure 5, which represents annual maximum temperature's amplitude. Despite a significant increase in most of the country, there are several microregions in the central region which face a temperature decrease, and others where there was just a small variation on the temperature.

[4] http://psleci.nic.in/




(a) Histogram. (b) Boxplot.

**Fig. 3**: Histogram and Boxplot of maximum temperatures for the year 2020. Source: India Meteorological Department.

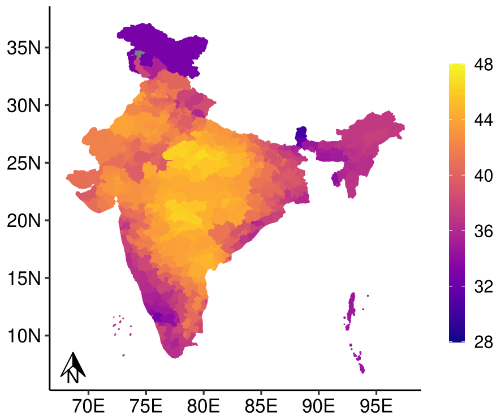



**Fig. 4**: Maximum temperatures for the year 2020. Source: India Meteorological Department.

Figures 6 demonstrates the minimum, the median and the maximum temperatures in the 70 years analyzed, showing a major concern, as in 27% of Indian's microregions there were temperatures above 45°C and 80% above 40°C per year. Those temperatures aren't consistent with the human body resistance to high temperatures. According to [26] human body resistance is within the limits of 36.1°C to $37,5$°C, depending on air humidity. Considering that the maximum annual temperatures observed in central India already exceed 40°C, that could represent a great risk of survival.

In this study, GEV was applied to model the 543 microregions, with the parameters $\xi, \lambda$ and $\delta$ estimated with the maximum likelihood method, and by testing the models with the Chi-Squared Test with 2 degree of freedom, the classes for the goodnessfit test were the quantiles 20%, 40%, 60% and 80% . The results showed that p-value was greater than 0,01 for 537 models, for the 5 rejected models the graphical tests were applied, which according to

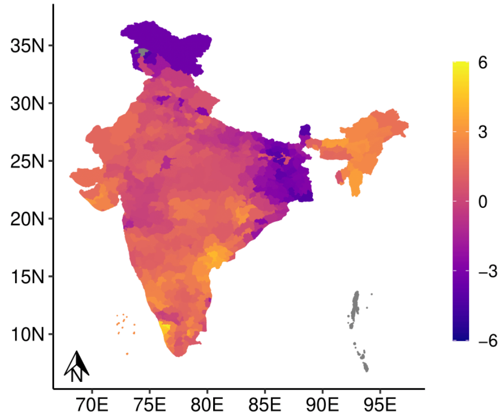
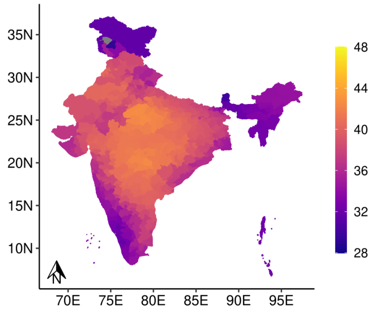
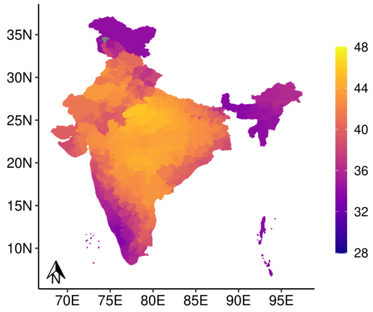


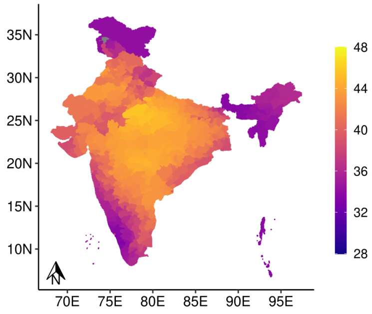

**Fig. 5**: Amplitude of annual maximum temperatures. Source: India Meteorological Department.




(a) Minimum.




(b) Median.




(c) Maximum.

**Fig. 6**: Minimun, Median and Maximum of annual temperatures. Source: India Meteorological Department.

Coles [21] are more suitable, the figures of the graphical tests for these models are attached. Resulting in four models that the GEV did not fit well and the Tonk - Sawai Madhopur, Ajmer, Pali, Jaunpur microregions was excluded from further analyses. In Figure 7 a boxplot of the p-values can be found.

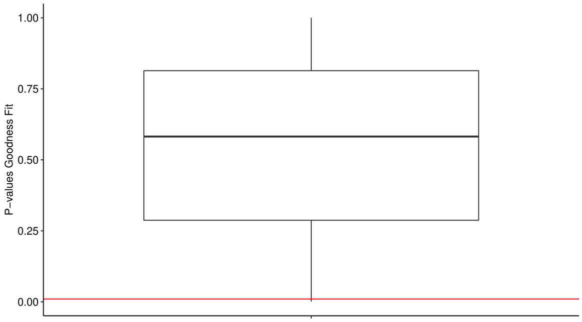



**Fig. 7**: P-values of the Chi-Square tests for all microregions. The author.

The GEV prediction power was tested (except the microregions of Andaman & Nicobar, Tonk - Sawai Madhopur, Ajmer, Pali and Jaunpur), the data were separated into two sets, data from 1951 to 2000 and from 2001 to 2020. With the data from 1951 - 2000, a GEV was modeled for each microregion and generated a forecast for the next 20 years. This value is compared with data from 2000 -2020. [21] states that the GEV forecast for $n$ years, in some year the observed value will exceed or be very close to the theoretical quartile $1-\frac{1}{n}$. Of the 538 GEV forecasts for the 20 years (2000 to 2020), 145 were higher than the real observed value, being 27% of the microregions. Figure 8 shows the boxplot of differences between observed and predicted values (Observed - Predicted).

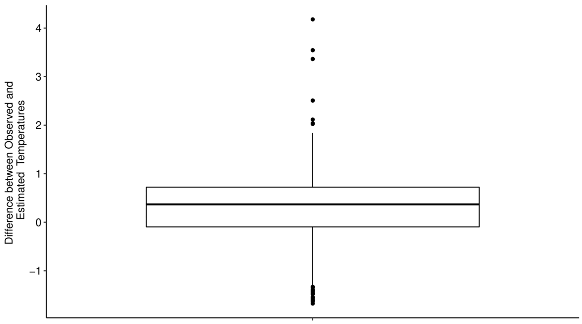
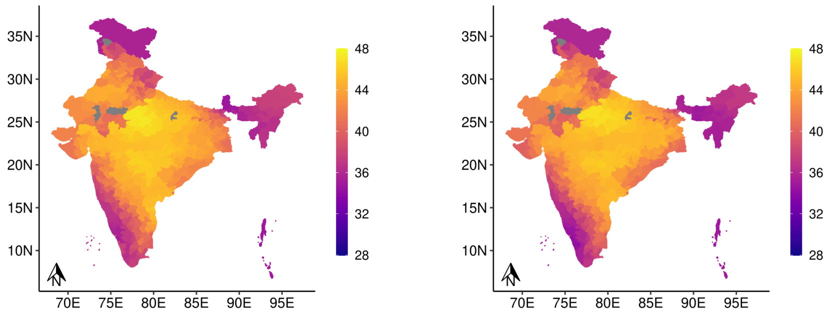



**Fig. 8**: Boxplot of the Difference between Observed and Estimated Temperatures

The GEV prediction power was considered satisfactory, 97% of predicted values were greater than observed values or the difference between them was less than 1, with a mean square error of 0.687. Figure 9 shows the observed and predicted values on the maps.




(a) Observed. (b) Predicted.

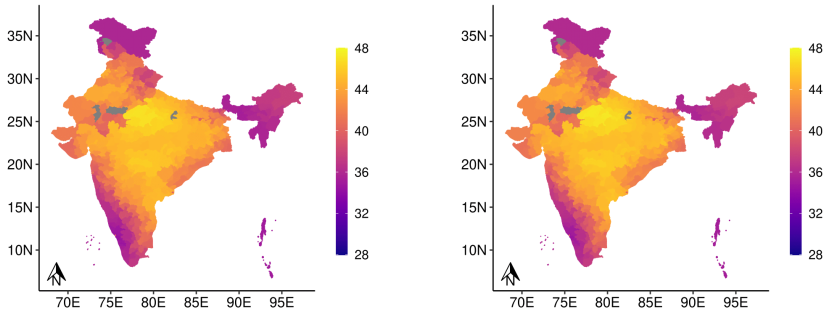
**Fig. 9**: Predicted and Observed Temperatures Of Maximum Temperature

The return level graphs for 20 and 50 years are presented in Figure 10. In the case of the former, the maximum value was 47.02°C and with 95% confidence interval extending from 46.84°C to 47.21°C while the minimum value was 34.33°C and with a 95% confidence interval extending from 34.09°C to 34.56°C. In the case of the 50 years return period, the maximum value was higher reaching 47.21°C and with 95% confidence interval extending from 47.00°$C$ to 47.41°C. The minimum value in thisd case was also higher (34.60°C) and with a 95% confidence interval extending from 34.32°C to 34.88°C.

Nevertheless, when compared with the chronology studied, there is a temperature decrease in some microregions, considering that. between 1951 and 2020. 32% of them had temperatures above 45°C. Despite that fact, the results are still worrying since the temperature's increase represent a risk for human survival.

# 5 Conclusion

With this study we aimed to estimate the main extreme parameters of interest according to the maximum annual temperatures in India's microregions, between 1951 and 2020. We developed a descriptive analysis materialized in thematic maps, which unveiled the worrying situation in Indian central region. Additionally, although in the East and Southwest regions the maximum temperatures were the lowest, it was where a higher increase was observed. Twenty seven percent of the microregions facing a temperature upper than 45°C, above the limit of human body resistance as we have seen.




(a) RL 20. (b) RL 50.

**Fig. 10**: Return Level of maximum temperature for periods of 20 to 50 years

Applied the adjustment quality test, 538 out of 542 models were proven to be effective.The predictive power of the models was tested and found to be satisfactory, with a mean square error of 0.687.

That enabled to develop return levels for 20 and 50 years, demonstrating that 22% of the microregions will face temperatures above 45°C if the authorities don't apply measures to fight and prevent this phenomenon.

# 6 Appendices

**Fig. 1**: Graphic test of the microregion of Bhadohi

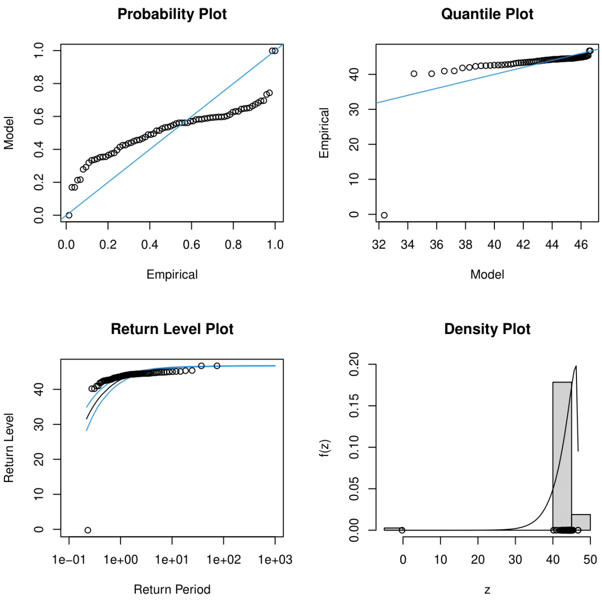


**Fig. 2**: Graphic test of the microregion of Jaunpur

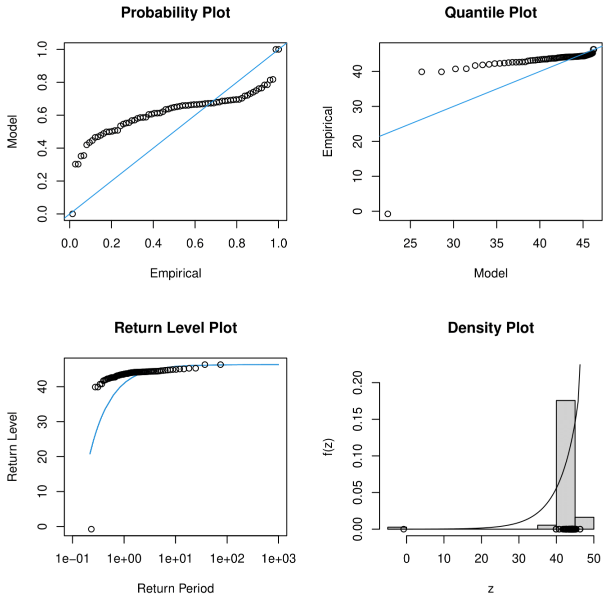



**Fig. 3**: Graphic test of the microregion of Pali

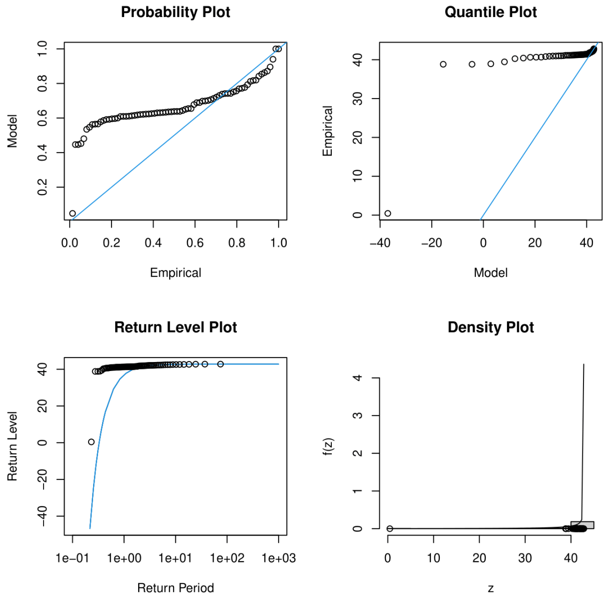


**Fig. 4**: Graphic test of the microregion of Tonk - Sawai Madhopur

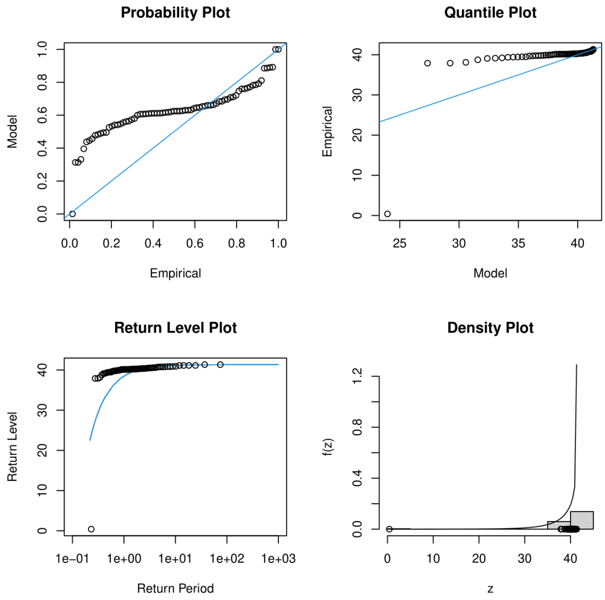
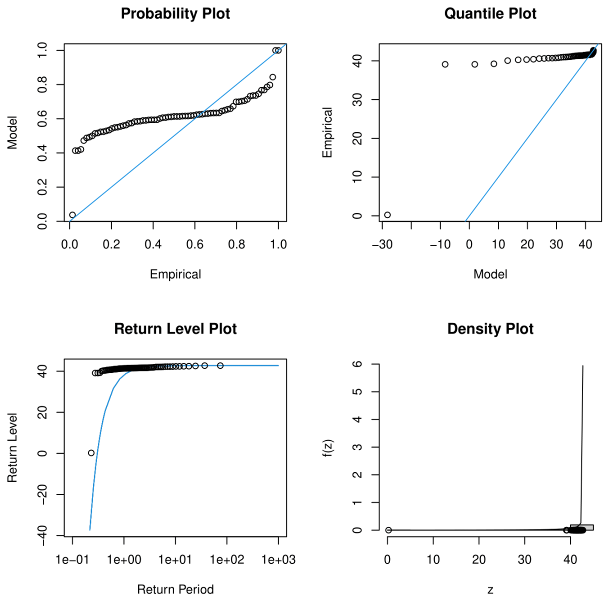



**Fig. 5**: Graphic test of the microregion of Ajmer



**Author Declarations.**

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**Competing Interests.** The authors have no competing interests.

**Ethics.** All authors have addressed the Ethics requirements and standards.

**Consent to participate.** All authors consent to participate.

**Consent for publication.** All authors consent for publication.

**Availability of data and material.** The datasets generated during and/or analysed during the current study are available in Supplementary Material.

**Code availability.** Not applicable.

**Author Contributions.** All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Venkata Dodla] and [G. C. Satyanarayana]. The first draft of the manuscript was written by [Flavio Ferraz Vieira], [Manuela Oliveira], [Eugénio Garção] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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