Analysis Of Temperature Changes and Extreme Heat Events in France, 2000–2024

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Abstract. In the last several years, global warming has become more apparent. France, being one of the most climate-sensitive regions in Europe, has been experiencing a clear rise in temperature and frequency of extreme heat, which has severely affected the public health, agricultural, and energy sectors. However, there has not been much systematic quantitative investigation of temperature trends in France over the past 25 years. On that basis, Copernicus ERA5 and ERA5-Land reanalysis datasets are utilized as baseline data sources, along with Météo-France official reports, to conduct a systematic examination of temperature change trends and spatial distribution of heat waves in France between 2000 and 2024. The annual mean temperature, summer mean temperature (JJA), number of hot days (Tmax > 35 °C), and TX90p indices were extracted using the ERA5 reanalysis data, and the trend of change was analyzed while using spatial interpolation and linear fit methods. The findings suggest that the overall warming trend rate in France is approximately 0.46 degrees Celsius per decade over the last 25 years, with the hottest years being 2003 and 2022 for heat waves. The southern coastal and southeastern coastal French areas experience the strongest warming. Generally, there was a high consistency between ERA5 data and Météo-France annual report results, with a very high correlation coefficient of greater than or equal to 0.9, and thus indicated the reliability of reanalysis data as a basis for regional climate monitoring.

Keywords: Climate change in France; ERA5; extreme heat; spatial distribution; temperature trend.

1. Introduction

Throughout the summers of 2023 and 2024, the national average temperature in France continually set new records for historical values, with many days experiencing an average daily temperature above 35°C [1]. Such events are not only hugely significant climatologically, but also have serious implications for public health, agricultural outputs, energy consumption, as well as infrastructure resilience. With its variety of landforms and climate, from the southern Mediterranean coast to northern plains and mountainous areas, France has significant differences in space, making it a particularly good laboratory for examining regional climate change. Thus, a systematic analysis of recent temperature change in France has a double purpose of enhancing the scientific understanding of climate change and providing the basis for policymakers to develop adaptation and mitigation strategies. Previous research mostly points to an unbroken trend of warming across France for the last several decades. Ribes et al. combined regional observations and CMIP6 models to assess the historical and future temperature change in France and found that human activity has markedly accelerated the warming [2]. Besson et al. generated a high spatial resolution daily extreme temperature dataset back to 1947 that shows a significant change in increase in extreme heat events, especially in the south and urban areas of the country [3]. Johannsen et al. examined the case of the urban heat island in Paris to show that urbanization enhances the intensity of extreme temperatures [4]. These previous studies provided the underpinnings of understanding warming in France but exposed weaknesses in visualizing short-term extreme events or variation in space. To overcome these weaknesses, the study presented here incorporates official Météo-France observations and Copernicus ERA5 reanalysis data and analyzes and visualizes temperature change in France systematically from 2000-2024. The aim here is to reveal recent warming characteristics, describe spatial heterogeneity, analyze the frequency of extreme heat events, and visualize regional disparities to provide an intuitive evidence base for climate research and communication to policy.

2. Data and Methods

This study combines reanalysis data, ground observations, and geospatial information to ensure that temperature variations across France are captured with sufficient spatial and temporal representativeness. Reanalysis data were used for quantitative analysis of long-term trends and spatial distribution, surface observations for validating the accuracy and consistency of reanalysis results, and geographic information to improve the spatial readability of maps.

The main source of climate data for this research is ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) [5, 6]. ERA5 datasets benefit from high spatial and temporal continuity and, therefore, can be utilized for climate change studies at the regional scale. The data are distributed by the Copernicus Climate Data Store (CDS), covering 2000–2024 with a spatial resolution of about 0.25° × 0.25°. The variable used is 2 m air temperature (t2m), which was processed uniformly in NetCDF format.

In addition, to improve the identification of extreme heat, this study also collected high-resolution ERA5-Land daily maximum temperature data (Tmax, ≈ 0.1° × 0.1°) for calculating summer extreme heat indices.

To verify the reliability of ERA5 data, annual climate assessment reports published by Météo-France, covering 2018–2024, were collected for comparison [1, 7]. These datasets include the national annual mean temperature, seasonal temperature anomalies, and statistics on extreme events, which are considered critical indicators of performance for ERA5 and ERA5-Land. Correlation analysis of these datasets against Météo-France observations allows an assessment of the applicability and stability of reanalysis products in France.

For spatial representation, France's geographic boundary data were obtained from the Natural Earth public database to show administrative boundaries and improve geospatial temperature-distribution maps [8]. All datasets were spatially registered and projected to the same coordinate system for consistency.

For data processing and calculations, hourly ERA5 temperature data were averaged to monthly and seasonal values. The national mean temperature was then computed using a latitude-weighted average, as follows:

$$\mathrm{Tmean} = \frac{\sum_{\mathrm{i}} \mathrm{Ti}\cos(\phi\mathrm{i})}{\sum_{\mathrm{i}} \cos(\phi\mathrm{i})} \tag{1}$$

In this context, Ti is the temperature at the grid and ϕi is its latitude. Summer mean temperature (JJA) refers to the value for the months of June to August. For the long-term change study, temperature anomalies were calculated relative to a 2000–2020 baseline determined from a fixed formula:

$$\mathrm{Anomaly(t)} = \mathrm{T(t)} - \mathrm{T2000} - 2020 \tag{2}$$

In this context, T(t) refers to the average temperature for the year t, and T2000–2020 is the multi-year mean for the years 2000–2020.

With respect to extreme heat indices, two variables were computed: TX35 (the number of days when Tmax > 35°C), reflecting absolute heat intensity, and TX90p (the proportion of days with Tmax exceeding the 90th percentile threshold of 2000–2020), reflecting relative frequency. TX35 characterizes the intensity of heat extremes and TX90p characterizes the frequency of relative heat extremes. Together these two extreme heat indices provide a summary measure of the overall strength and frequency of heatwaves in France.

It completed data processing, calculation, data visualization using Python, and associated scientific computing and visualization libraries like (x-ray, NumPy, matplotlib, and geopandas). During mapping, we used several software approaches to obtain the temperature fields that were accompanied by French administrative boundaries to maximize spatial readability and clear visualization.

3. Results and Analysis

3.1. Trends in France’s Annual Mean Temperature

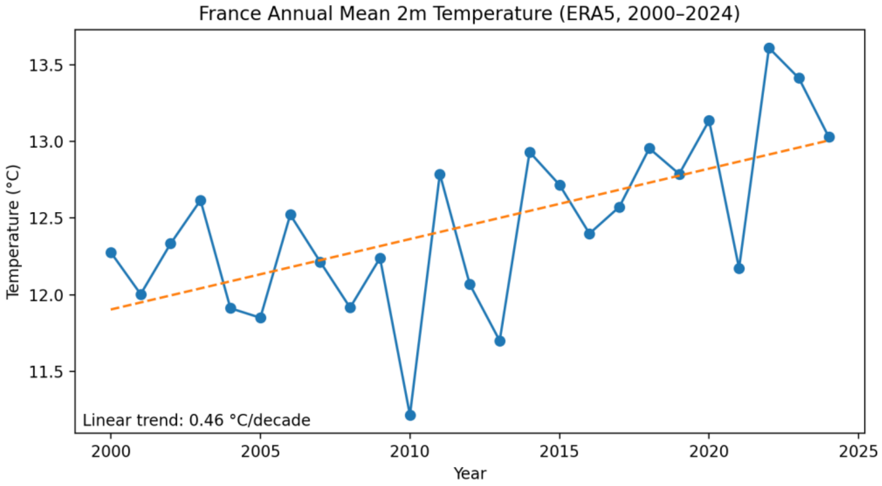

Fig. 1 France Annual Mean 2m Temperature (ERA5, 2000–2024) (Photo/Picture credit: Original).

France’s average annual 2 m temperature from 2000 to 2024 is shown in Fig. 1. The horizontal axis is the year and the vertical axis is the annual mean temperature (°C). The blue marks denote the data collected for each year and the red line indicates the linear trend. Overall, there is a considerably large positive trend in temperature at a rate of approximately 0.46 °C per decade. Before 2010, the temperature changes were pretty high, but the increase has been to steadily increasing in temperature since 2015. Both 2022 and 2023 were very warm years in the record period. This is an indication that there has been a uniform and accelerated warming pattern in France in the past 25 years, especially in comparison to other areas in Europe.

3.2. Spatial Distribution of Summer Temperature Anomalies

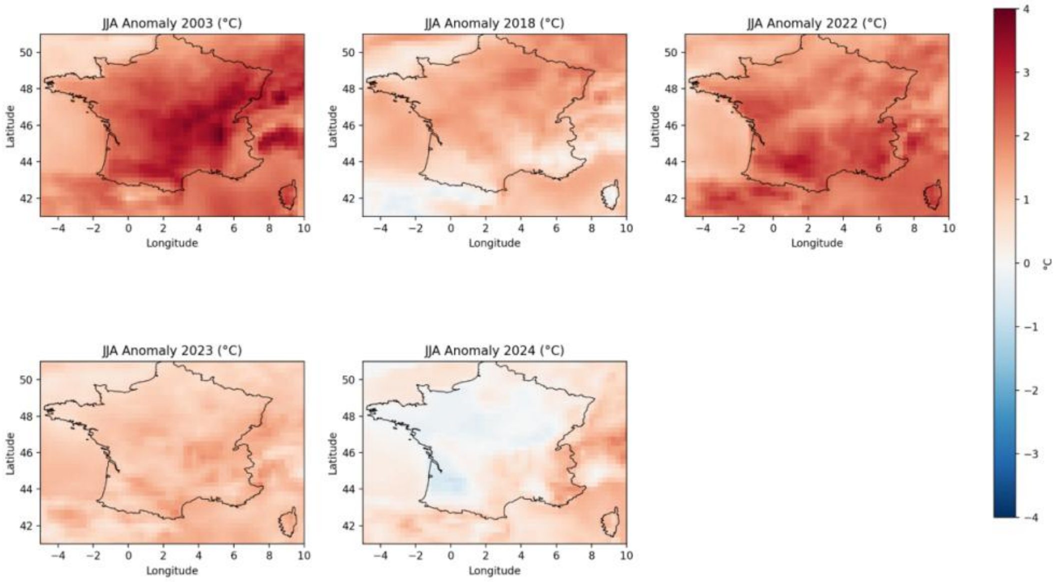

Fig. 2 France JJA 2m Temperature Anomaly vs 2000–2020 (ERA5 monthly) (Photo/Picture credit: Original).

The spatial distribution of summer (JJA; June - August) temperature anomalies for 2003, 2018, 2022, and 2023 is shown in Fig. 2, relative to the 2000-2020 baseline. Longitude and latitude are indicated on the horizontal and vertical axes, respectively. Red areas indicate positive anomalies (warmer than average) while blue areas indicate negative anomalies (cooler than average). The greatest anomalies occurred during 2003 and 2022, with central and southern areas more than 3 °C warmer than the baseline, particularly in Provence and Languedoc. The warming area was smaller in 2018, and in 2024, there were areas in the southwestern coast and the Massif Central that had slightly negative anomalies. In general, the spatial pattern of French summer warming can be summarized as "stronger in the south and inland, weaker in the north and along coasts" due to the effects of very hot dry air masses from the Mediterranean and the heating effects of topographic subsidence.

3.3. Distribution of Extreme Hot Days

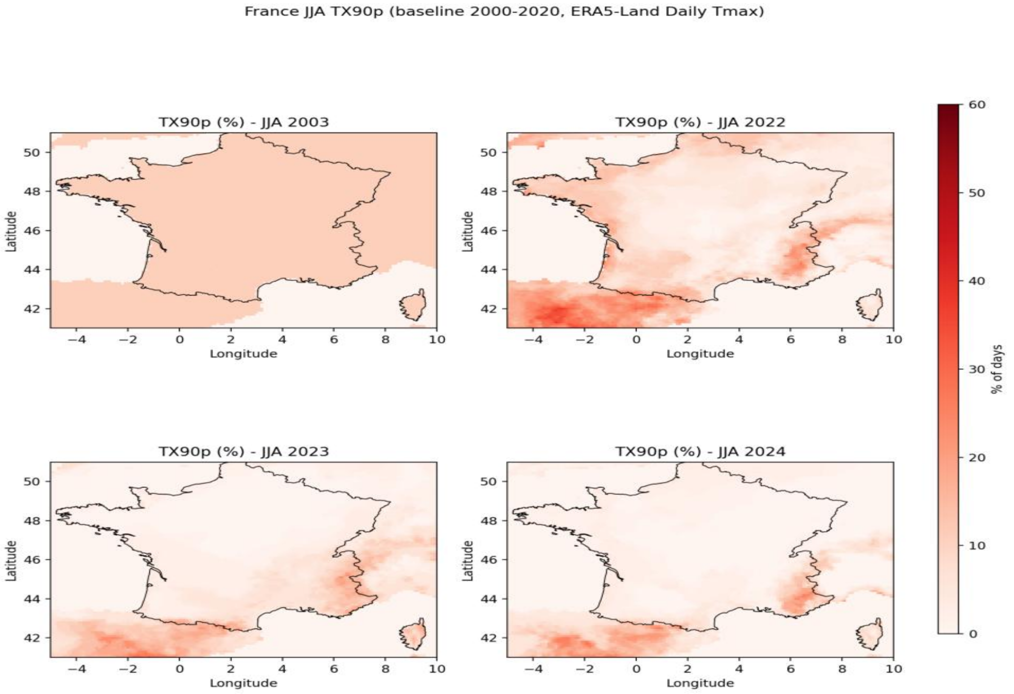

Fig. 3 Spatial Distribution of France JJA TX90p (Photo/Picture credit: Original).

Fig. 3 shows the geographic pattern of summer days with Tmax over 35 °C. The color gradient shows the number of hot days (days). Summer hot days in the present study are mostly situated in the southern and southeastern coastal regions of the country, and particularly in Provence, Languedoc, and the mountain foothills of the Pyrenees, where the number of hot days exceeded 30. The central region of the country typically saw an average of 10–20 hot days. The northern regions and Atlantic coast, which are affected by the ocean, saw a maximum of less than 5 days of Tmax exceeding 35 °C. Extreme heat events were worst in 2003 and 2022 for France, with the extremes noted for these places mostly along the Mediterranean Coast, consistent with Besson's observations that shows a spatial concentration of extreme heat events in Mediterranean-type regions [9].

3.4. Spatial Distribution of TX90p Extreme-Heat Frequency

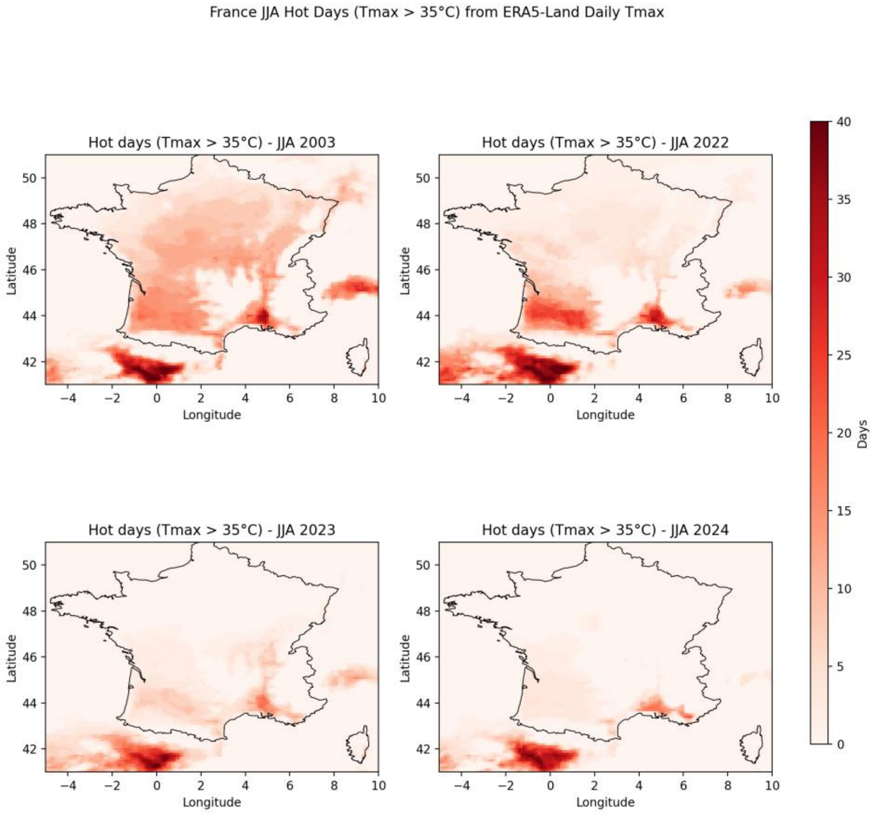

Fig. 4 France JJA Hot Days (>35°C) (Photo/Picture credit: Original).

Fig. 4 illustrates the monthly distribution of the TX90p index, which is the percentage of days during summer (JJA) in which TMmax is above the 90th percentile of the 2000–2020 baseline. Darker hues represent areas with more frequency extremes in heat. The analysis indicated that 2003 and 2022 again exhibited the highest TX90p values beyond 50%, or more than half of summer days witnessed extreme heat. Even though 2018 and 2023 exhibited TX90p values that were slightly lower, they still exhibited large TX90p regions, more so in the southeastern coastal regions and the Rhône Valley. In 2024 the frequency was slightly diminished, but southern and eastern France depicted regions of extreme heat intensity. For these reasons, there is evident consistency of intensification of extreme heat events in southern and southeastern France.

3.5. Changes in Extreme Heat Across Latitudinal Zones

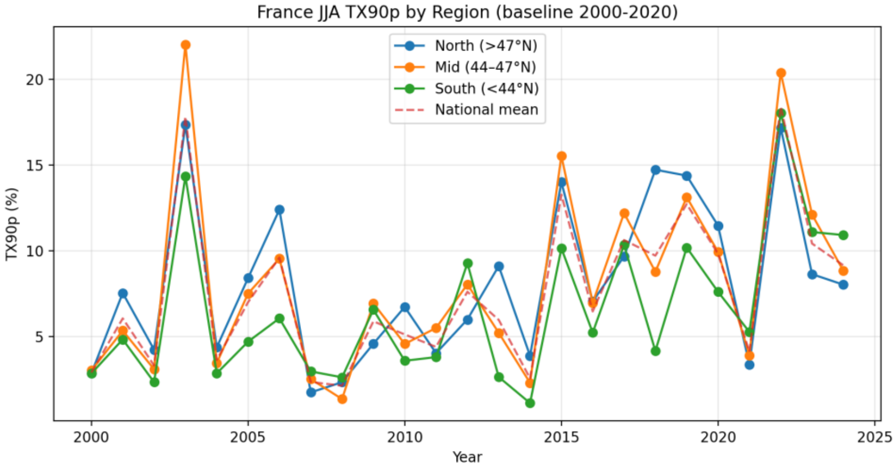

Fig. 5 France JJA TX90p by Region (Photo/Picture credit: Original).

Fig. 5 presents the interannual variation of TX90p across France's latitudinal regions. The horizontal axis indicates year (2000–2024), and percentage of TX90p is noted on the vertical axis. The red line is for the southern region, which is located < 44° N, the blue line is for the central region, which is located 44–47° N, and the green line is for the northern region, which is located > 47° N. The dashed line denotes the national mean. The results show that the southern region had the highest values and had the most variability, which would imply frequent heatwaves that were long-lasting. The central area had a similar trend to the national means, suggesting that the majority of central France entered, in general, a warmer climate regime. The northern area had lower overall values; however, there was an upward trajectory in the data since 2015, which would suggest that the effect of extreme heat is likely expanding further north. In the national mean curve, the vast inter-decadal fluctuation/peaks in extreme heat events in France were evident in 2003, 2015, and 2022. The fact that different regional curves peak at similar durations demonstrates the national spread of an extreme heat phenomenon.

4. Discussion

4.1. Regional Differences and Climatic Drivers

The increase in temperature and distribution of extreme heat across France show underlying regional differences. Using ERA5 and ERA5-Land data, the area with the most warming is located in southern and southeastern coastal France (Mediterranean climate zone), then the central and southwestern plain regions, while the northern and coastal regions are least affected. The South West where the subtropical high-pressure system is prominent, shows an intense adiabatic warming process under subsidence conditions in summer, where in terms of the surface energy balance the balance shifts to sensible heat flux to further exacerbate the warming process [5, 10]. Conversely, as mentioned the northern region and in the Atlantic coastal areas, the nudging and moderating effects of the ocean associated with the warming is less. Additionally, the urban heat island effect is especially pronounced in metro regions like Paris, Lyon, and Toulouse, where it exacerbates local heating trends [10].

4.2. Interannual Characteristics of Extreme Heat Events

Examination of hot day counts and TX90p indices indicates that extreme heat events in France have intensified since the year 2000. 2003 and 2022 are representative peak years; the southern and eastern areas were stressed more than other regions because of an established continental area of high pressure, the northward shift of the westerlies, and exacerbated drought conditions [1, 8]. The year 2023 showed a slight temperance; however, high TX90p values remained in the south, and also on the Mediterranean coast; thus, extreme heat has emerged as a recognized climatic feature. In sum, the summer climate in France is transitioning toward 'hotter, drier, and more extreme,' in alignment with IPCC Synthesis Report outcomes [1, 7].

4.3. Consistency Analysis between ERA5 and Météo-France Data

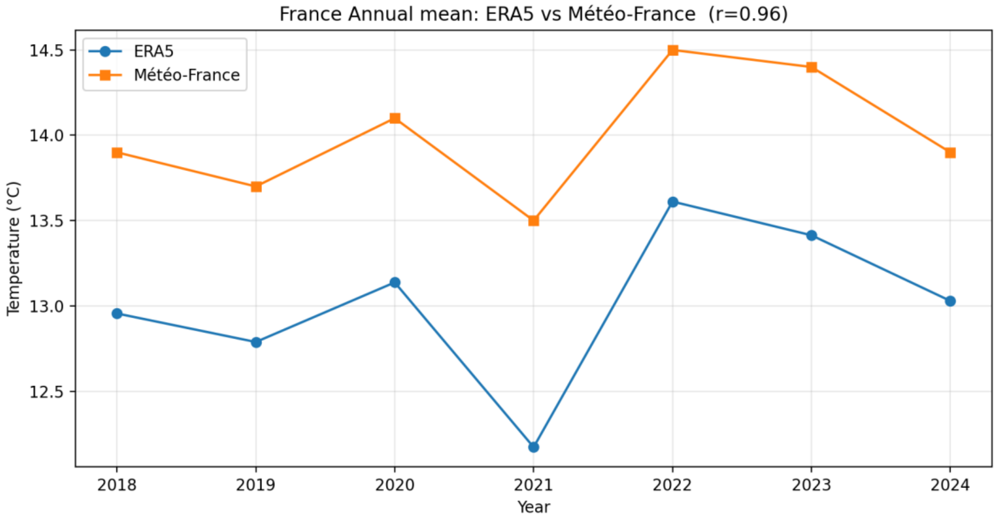

Fig. 6 ERA5 vs Météo-France (Annual Temperature) (Photo/Picture credit: Original).

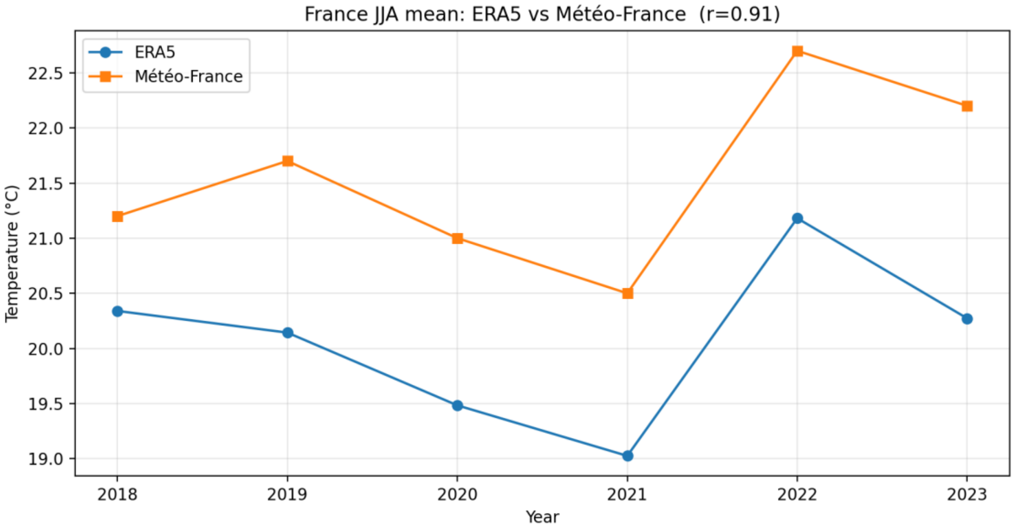

Fig. 7 ERA5 vs Météo-France (JJA Temperature) (Photo/Picture credit: Original).

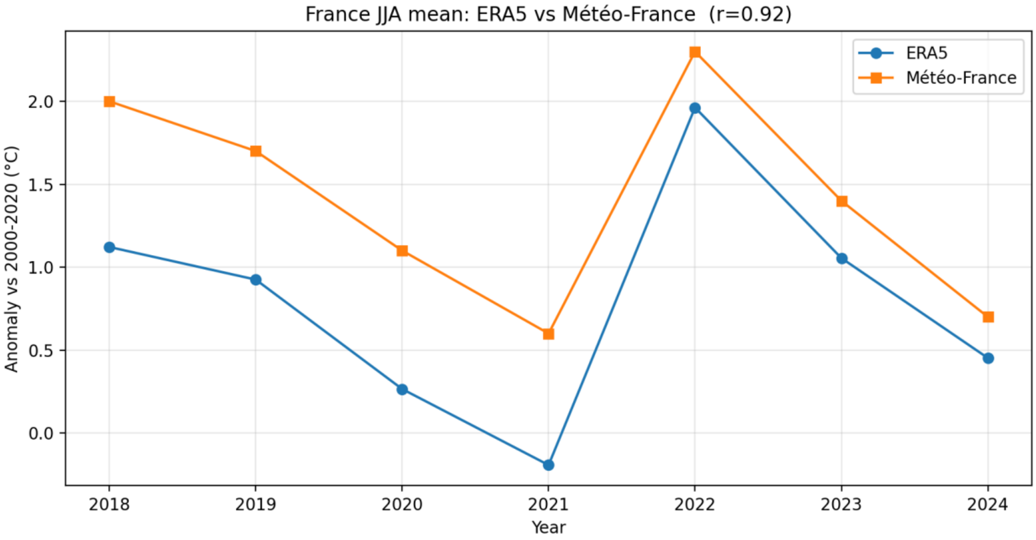

Fig. 8 ERA5 vs Météo-France (JJA Anomaly) (Photo/Picture credit: Original).

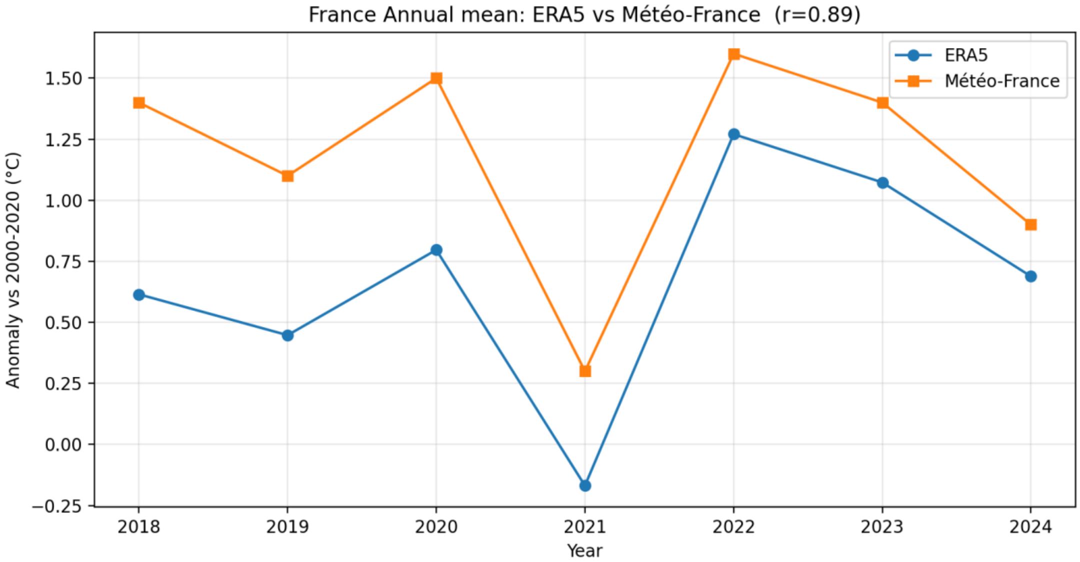

Fig. 9 ERA5 vs Météo-France (Annual Anomaly) (Photo/Picture credit: Original).

To assess the reliability of the ERA5 data, this work compared the ERA5 annual mean temperature to the annual report results from Météo-France. As shown Figs. 6-9, the two datasets demonstrate very similar annual and summer temperature trends, with values of r = 0.96 and r = 0.91 -- thus showing that the ERA5 represents the warming patterns of France well. The absolute ERA5 temperatures are slightly lower, roughly 0.5–1 °C lower, likely owing to the limited spatial resolution (0.25°) of the model, which limits the ability to represent urban and mountain microclimates and differences between the surface parameterizations in the ERA5-Land model and measurements [5, 6]. In general, this difference would not influence the trends reported here, but interpretations of extremes should be done with caution.

4.4. Research Limitations

The present study comprehensively examined temperature change and heat extremes in France from 2000 to 2024, which still presents certain limitations. While the spatial resolution of ERA5 and ERA5-Land is sufficient for estimating trends on national scales, they have limitations when it comes to resolving fine-scale characteristics over complex terrain, such as what is found in the Alps and Pyrenees [5, 8]. Concerning extreme climate indicators, this study used TX90p and a fixed threshold of 35 °C to quantify extreme heat without analyzing indicators such as heatwave duration, nighttime temperature, or other compound indices [8]. Lastly, this study has primarily focused on physical climatic processes without an in-depth analysis of societal impacts. For instance, according to Pascal et al., heat-related mortality in France rose markedly from 2014 to 2023, even when controlling for changes in temperature, indicating a growing societal toll of climate warming [2].

4.5. Outlook

In-depth investigations show that the temperature and extreme heat events across France from 2000 and onwards have increased significantly, with regional variability—particularly in the southern and south eastern coastal regions. Future studies should follow-up on higher spatiotemporal resolution and inter-disciplinarity. Initially, the temporal extent of climatic series should be prolonged to enhance analyses, as well as employing high-resolution reanalysis datasets and regional climate models to expand understanding of nonlinear warming trends across France’s diverse geographies [5, 8]. Secondly, assimilations and fusions of reanalysis products with ground-based observations should be strengthened to improve detection and calibration of extreme events, creating simulations and projections that are more reflective of observation and reality [6, 8]. Moreover, studies of climate should increasingly address the social implications of warming to expand adaptive-capacity and social vulnerability indicators into a climate assessment framework, creating multi-directional space for climate and social sciences to work conjunctively to continue to provide the public and policymakers with evidence-based public health protection; [1, 3, 8].

5. Conclusion

Using ERA5 and ERA5-Land datasets as well as the annual climate reports produced by Météo-France, this research provided a systematic assessment of temperature changes and extreme heat in France for the years 2000–2024. The analyses show that, over the last 25 years, average temperatures have increased markedly overall, at a rate of roughly 0.46 °C per decade, with heat intensity in summer independently increasing. The years 2003 and 2022 were identified as the hottest years, with extended heatwave coverage across the country and with regions exceeding 30 hot days over the year. Geographically, the largest warming was observed in southern and southeastern coastal areas (i.e., Provence, Languedoc, and coastal Mediterranean), whereas northern and coastal areas warmed at a slower rate due to ocean regulation and moderation of temperature. An examination of the extreme temperature index (TX90p) indicated that both the frequency and duration of extreme heat had also significantly increased in southern France and that, although regions in the central part of the country continued to show upward trends, the overall warming trend is now demonstrating national levels of warming. Furthermore, the two datasets between ERA5 and Météo-France had a very high degree of agreement, including an annual and summer mean temperature correlation of 0.96 and 0.91, respectively, demonstrating the reliability of the datasets to represent climate changes at regional scales.

However, limitations exist: ERA5's resolution does not sufficiently resolve a number of local effects on complex topography, such as the Alps and Pyrenees; the dataset used a limited set of extreme indices (missing heatwave duration and nighttime extremes); and there is no direct socioeconomic consideration, such as energy use, health risks, and productivity change.

Future work could be pursued in three ways: (1) the use of a higher-resolution reanalysis and regional climate model (for example, EURO-CORDEX) to improve the precision of climate simulation spatially over complex terrain; (2) the extreme climate indices could be broadened by adding heatwave metrics such as HWMI, HWD, TXx and others; (3) combined datasets in climate and socioeconomic domains could be generated to create an interlinked climate-related risk assessment framework that provides quantitative evidence for climate policy in France and Europe. Overall, the study advances our understanding of France's warming characteristics, and offers a rigorous scientific framework to substantiate reliability of reanalysis datasets in regional climate applications.

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