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SPATIOTEMPORAL ASSESSMENT OF GLOBAL SURFACE TEMPERATURE TRENDS UNDER CLIMATE CHANGE

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Abstract

The long-term spatial and temporal trends in global land-surface temperature were evaluated by using historical monthly observations at the global, country, state/province and major-city level. The research methodology used was quantitative, retrospective and observational. All the temperature data were cleaned and processed using Python and then analysed using descriptive statistics, linear regression, the Mann–Kendall trend test and Sen's slope estimator at the annual, seasonal and decadal scales. The temperature anomalies were based on the 1951-1980 base period. The global dataset included data for 1750-2015; the spatial dataset included data for 242 countries, 241 states or provinces and 100 major cities up to 2013. Global land temperature showed statistically significant rising trend; linear regression showed a warming trend of 0.0458 °C/decade, whereas Sen's slope showed warming trend of 0.0516 °C/decade. The warmest decade was the 2010s and the warmest year was 2015 at 1.173 °C. Significant warming was found during all seasons with the greatest rate of warming occurring in autumn at 0.0652 °C per decade. The mean warming rates for countries, states or provinces and major cities were 0.0702 °C per decade, 0.0643 °C and 0.0694 °C respectively. These results confirm warming that has occurred, but also in a regionally variable manner, and point to the need for long-term monitoring for regionally based assessments of climate risk, adaptation planning and evidence-based policymaking.

Keywords: climate change; land-surface temperature; spatiotemporal analysis; temperature anomalies; warming trends

1. Introduction

Global climate change is manifested by permanent changes in the Earth's climate system, which are mainly due to human greenhouse gas emissions, industrialization, deforestation, and high energy consumption. A clear sign of this process is the increase of surface temperature, which is related to the long-term variation in the energy balance of the atmosphere and land surface (Gulev et al. 2021; Masson-Delmotte et al. 2018). Over the past few decades, several of the warmest years on record have occurred, suggesting that global warming is not a transient phenomenon but it is a climatic trend (Arguez et al. 2020). While there may be some short-term variability due to natural causes like solar variation, the overall trend in recent warming is strongly linked to human activity (Connolly et al. 2021). The temperature rise has led to ecological disturbances, glacier loss, sea level rise, heatwaves, changes in rainfall, stress to agriculture, health risks and economic losses. Warming in the ocean has also increased, reinforcing the trend of increased heat storage in the climate system (Cheng et al. 2019, 2022). Ocean temperatures in 2020, 2021, and so on continue to record sustained global warming (Cheng et al. 2021, 2023).

Surface temperature assessment is crucial for the evaluation of climate change, as temperature affects agriculture, the availability of water resources, ecosystems, public health and the risk of disasters. Historical temperature records can be used to help distinguish between temporary variability and persistent climate change, and to evaluate the performance of climate models (Hausfather et al. 2020). Researchers can use reliable temperature monitoring to also pinpoint areas that are more vulnerable and warm-up spells. Warming across the atmosphere, land and oceans has been observed in annual climate indicators, highlighting the importance of systematic observation and regular updates of climate evidence (Forster et al. 2023, 2024).

There is spatial and temporal variation in temperature change. The warming rate varies from country to country, state to state, and city to city due to the latitude, elevation, land cover, urbanization, and climatic conditions of the area. Built-up surfaces in urban areas and a lack of vegetation, as well as the effect of higher latitudes, lead to greater warming in these areas. There is also variation at seasonal and annual scales and temperature must be considered on these scales as well. An additional value of annual, decadal and seasonal analysis is that the nature of observed changes can be seen as being transient or persistent. Real-time warming indicators and historical reconstructions have shown that positive warming anomalies have been continuously growing beyond the previous climatic conditions (Haustein et al. 2017).

Long-term datasets can help support a robust assessment of climate trends because they contain consistent observations over longer time periods. At the global level, country, state, and urban level, warming trends can be analyzed at a variety of spatial scales. Geographical co-ordinates are useful for mapping and comparison with other regions and uncertainty estimates can be used to assess the reliability of the historical observations. Development of the new datasets, e.g., HadEX3 and ERA5, has enhanced climate monitoring in terms of spatial coverage, continuity and comparability (Dunn et al. 2020; Hersbach et al. 2020). Technical climate summaries also highlight the need for clear and consistent observational data to gain insight into long-term climate change.

While there have been numerous studies reporting global warming, only few have combined global, national, state, and major city observations within a single analysis. Previous studies tend to either concentrate on one geographical level or one temporal scale. This makes it difficult to compare annual, decadal, seasonal and spatial patterns. Thus a joint evaluation is required to be able to determine areas where the warming rate is relatively high, and to be able to compare warming trends across geographical scales. This study investigates global land surface temperature trends over the long term, quantifies annual, decadal and seasonal variations, shows the differing warming over countries, states and major cities, pinpoints the highest rates of warming and estimates the uncertainties and missingness in the historical temperature record.

2. Materials and Methods

2.1 Research Design

The type of this research was quantitative, retrospective and observational study with secondary data on historical temperature. A longitudinal and spatiotemporal analysis approach was used to evaluate the changes in LST at global, country, state, major city and city scales.

2.2 Dataset Description

Five CSV files were used. GlobalTemperatures.csv was the file with global monthly land-temperature data from 1750 to 2015 with average, minimum, maximum and land-ocean temperatures. The spatial datasets had location identifiers, and latitude and longitude were provided for the city datasets (Earth 2016).

2.3 Study Variables

Average temperature, minimum temperature, maximum temperature, land–ocean average temperature and temperature uncertainty were the main variables. Temporal variables were date, season, year, decade and year. Spatial variables were country, state, city, latitude and longitude. The derived variables were annual mean temperature, seasonal mean temperature, temperature anomaly, and warming rate (in °C per decade).

2.4 Data Selection Criteria

Records that had a valid date, determined location and available temperature were included. Duplicate observations, invalid dates, missing temperature records and unidentified locations were removed. The locations where the number of annual observations was less than 30 years were not included in long-term trend analysis.

2.5 Data Pre-processing

All the datasets were imported and processed using Python. The date variable was transformed to datetime format and the year, month, season and decade of the date were created. Directional text was converted to numeric signed latitude and longitude. Duplicate records were eliminated and names of locations were standardized. If temperatures were missing, these were not included in the principal analysis. The annual averages were only computed when a minimum of 10 monthly values were available for the location for the year.

2.6 Temperature Aggregation and Anomaly Calculation

The monthly data were used to create annual, seasonal and decadal means. The seasonal classification was modified to cater for the Northern and Southern hemispheres. The temperature anomalies were computed based on the mean 1951 – 1980. The difference between the annual temperature and the baseline temperature was calculated to see the anomaly.

2.7 Statistical Analysis

The descriptive statistics used were mean, median, standard deviation, minimum, maximum, range, and interquartile range. The absolute rates of change of temperature for each decade and each year were estimated using linear regression. Mann-Kendall test was used to detect significant monotonic change and Sen's slope was used to estimate the magnitude of change in temperature. The 95% confidence interval with p-value < 0.05 was considered statistically significant. Identify similarities and differences between two or more locations and physical features.

2.8 Spatial and Comparative Analysis

Warming rates were computed for countries, states, major cities and cities. Pearson or Spearman correlations were analysed to assess the correlation between year and temperature, latitude and average temperature, latitude and warming rate, and temperature and uncertainty. To compare the temperature patterns between decades, seasons, geographical region and latitude zones, analysis of variance or Kruskal–Wallis test was applied.

2.9 Software and Data Visualization

All data cleaning, statistical analysis and visualization were done in Python. The primary libraries used were Pandas and NumPy for data handling, SciPy and Statsmodels for statistical analysis, PyMannKendall for trend testing, and for graphical plots and spatial maps, Matplotlib, GeoPandas and Plotly were used. Annual trend lines, anomaly plots, decadal comparisons, seasonal trend graphs, scatter plots by latitude, heatmaps and warming maps by country/city were the visual outputs produced.

3. Results

3.1 Dataset Characteristics

Four sets of historical temperature data were analysed, including Global, Country, State and Major City temperature data. Data from the global dataset were cleaned for 3,180 valid monthly observations out of 3,192 observations (99.62%) during the period 1750–2015. The country-level data contained 577,462 observations from 242 countries, while the state-level data contained 645,675 observations from 241 states or provinces. The major-city dataset contained 239,177 monthly observations from 100 major cities in 49 countries. Data completeness was overall high with the percentage of missing temperature observations varying between 0.38% in the global dataset and 5.65% in the country-level dataset. The summary of the characteristics of the four temperature datasets used in the analyses is given in Table 1, which shows the number of observations used, data completeness, temporal and geographical coverage.

Table 1. Dataset Characteristics and Analytical Coverage.

Dataset	Original observations	Valid observations	Missing temperature, n (%)	Temporal coverage	Geographical units
Global temperature	3,192	3,180	12 (0.38)	1750–2015	1
Country-level temperature	577,462	544,811	32,651 (5.65)	1743–2013	242
State-level temperature	645,675	620,027	25,648 (3.97)	1743–2013	241
Major-city temperature	239,177	228,175	11,002 (4.60)	1743–2013	100

3.2 Global Temporal Temperature Trends

Annual global land-temperature records showed a statistically significant long-term warming trend for the entire study period (1750–2015). The estimated mean warming rate was 0.0458 °C per decade with the regression model accounting for 38.4% of the temporal variation (R2 = 0.384; $p < 0.001$). There was a significant increasing trend as evidenced by the non-parametric Mann–Kendall test ($Z = 11.558$; $p < 0.001$). In the same way, Sen's slope estimator yielded a median warming rate of 0.0516 °C per decade with a 95% confidence interval between 0.0436 and 0.0598 °C per decade suggesting a stable warming rate on global land. Figure 1 shows the annual global land temperature trend for 1750-2015, and the 10-year moving average trend and fitted linear trend.

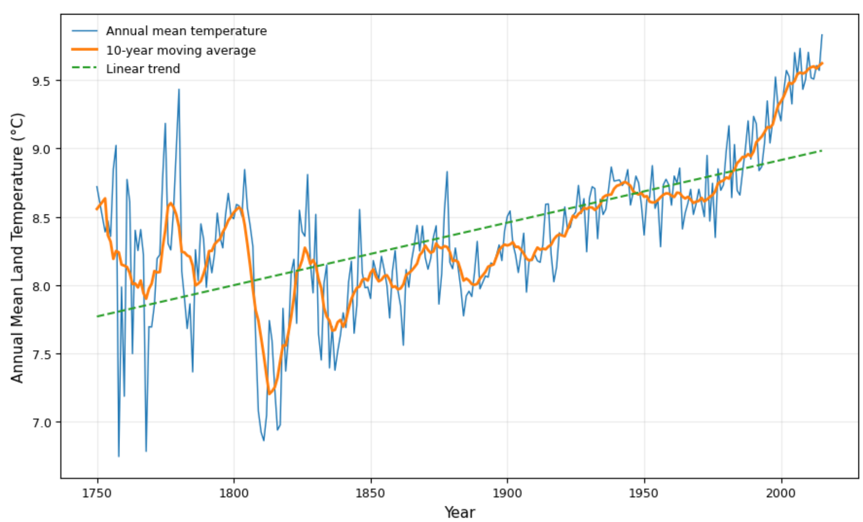

Figure 1. Annual Global Land Temperature Trend

Table 2 presents the principal findings of the global temporal trend analysis, including linear regression results, Mann–Kendall statistics, Sen's slope estimates, temperature anomalies, and seasonal warming characteristics.

Table 2. Summary of Global Temporal Temperature Trends

Indicator	Result
Analytical period	1750–2015
Annual observations	264
Linear warming rate	0.0458 °C/decade
Linear trend R^2	0.384
Linear trend p-value	<0.001
Mann–Kendall Z	11.558
Mann–Kendall p-value	<0.001
Sen's slope	0.0516 °C/decade
Sen's slope (95% CI)	0.0436 to 0.0598 °C/decade
Highest anomaly	1.173 °C (2015)
Lowest anomaly	−1.914 °C (1758)
Warmest decade	2010s (9.622 °C)
Fastest-warming season	Autumn (0.0652 °C/decade)

3.3 Global Temperature Anomalies and Decadal Changes

The long-term variations of temperature anomalies with respect to the 1951–1980 normal period were quite large. The highest positive anomaly was observed in 2015 (1.173 °C) and the most negative anomaly was in 1758 (−1.914 °C). The anomaly series showed an upward trend in the frequency of positive anomalies in the last few decades, and thus a warming trend. Decadal averages also showed a steady increase in global land temperature, and the decade of the 2010s had the highest average temperature of 0.09622 °C. Previous decades had slightly lower mean temperatures, reflecting the shift of temperature towards warmer climate over the past history. The global temperature anomalies are shown for each year since 1950, in comparison to the 1951-1980 baseline period, in Figure 2 which shows both long-term variations and the frequency of positive anomalies.

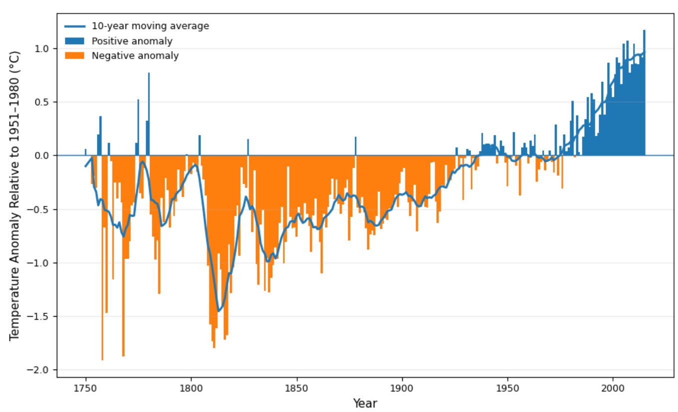

Figure 2. Global Annual Temperature Anomalies

Figure 3 presents the decadal variation in global mean land temperature, illustrating the long-term progression of warming across successive decades.

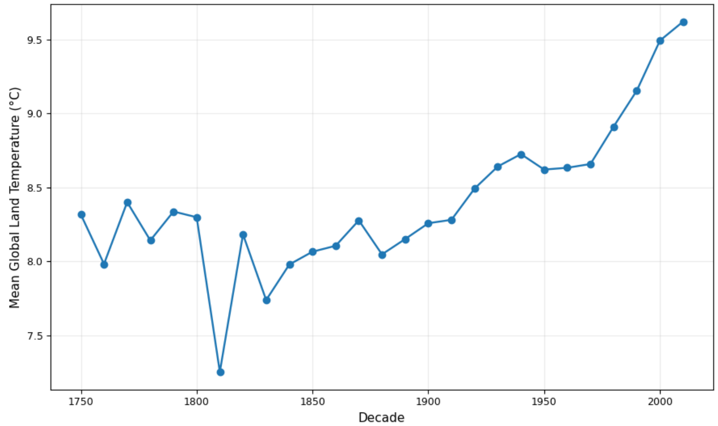

Figure 3. Decadal Global Land Temperature Trend

3.4 Seasonal Temperature Trends

Seasonal trend analysis revealed that there was a warming trend in all four seasons over the study period. Autumn showed the largest warming rate (0.0652 °C per decade) and winter had a similar rate (0.0622 °C per decade). The warming rates for spring and summer were relatively low, with 0.0370 °C per decade and 0.0197 °C per decade, respectively. Seasonal warming has been consistently observed over the historical period irrespective of season with statistically significant increasing temperature trends ($p < 0.001$) for all seasons as indicated by Mann–Kendall trend analysis.

3.5 Comparison of Spatial Warming Trends

Warming at the country, state/provincial, and major-city levels was always seen when comparing the different spatial scales. The warming rate by countries (0.0702 °C per decade) was the highest, followed by major cities (0.0694 °C per decade) and states or provinces (0.0643 °C per decade). Median warming rates were between 0.0600 and 0.0771 °C per decade, with maximum warming rates up to 0.1471 °C per decade at the country level. For the 242 countries, 241 states/provinces and 100 major cities analysed, the warming was found to be statistically significant in all. The estimated warming rates at the country, state/Provincial and major-city levels are compared in Table 3 using Sen's slope statistics.

Table 3. Comparison of Spatial Warming Trends

Geographical level	Units analysed	Mean warming rate (°C/decade)	Median warming rate (°C/decade)	Minimum warming rate (°C/decade)	Maximum warming rate (°C/decade)	Units with significant warming
Country	242	0.0702	0.0771	0.0254	0.1471	242
State or province	241	0.0643	0.0600	0.0310	0.1176	241
Major city	100	0.0694	0.0747	0.0255	0.0988	100

Figure 4 compares the average warming rates across different geographical levels, including the global, country, state/provincial, and major-city scales.

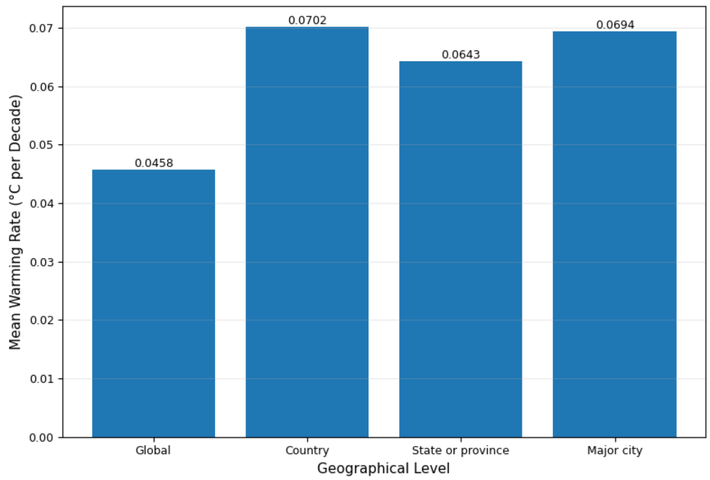

Figure 4. Mean Warming Rates Across Geographical Levels

Overall, the findings demonstrated a consistent and statistically significant long-term warming trend across global, country, state/provincial, and major-city levels, with recent decades exhibiting the highest temperatures and the most frequent positive anomalies. Spatial comparisons further indicated that although warming rates varied among geographical levels, all analysed regions showed significant warming, highlighting the widespread nature of contemporary climate change.

4. Discussion

The study revealed a robust and statistically significant global warming trend over the historical period at the land surface. The greatest warming has taken place in recent decades, and positive temperature anomalies increased in frequency after the late twentieth century. In space, warming was observed in countries, states and major cities, but with varying magnitudes. There was even an increase in warming during autumn and winter compared to spring and summer. This is in line with the overall conclusion that the recent climate change is widespread, persistent and mainly linked to anthropogenic forcing (Lee et al. 2023).

This warming trend is an indication of long-term climate change, not short-term fluctuations. Years exhibited sporadic cooling or warming, but the overall trend was positive throughout the entire year. A significant number of positive anomalies in recent years suggests that the current temperature is increasingly exceeding the previous baseline temperature. This is the same pattern as evidence that has revealed that climate change signals can now be discerned even in short-term weather fluctuations (Sippel et al. 2020). This is consistent with the revised observational data which show a long-term warming of the near-surface atmosphere since the 1800s (Morice et al. 2021).

A comparison of average temperatures across decades revealed that the last few decades were definitely warmer than previous ones. This acceleration due to a combination of the effects of greenhouse-gas emissions, industrial expansion, and the use of fossil fuels. Warm and cold periods in the past were not synchronous globally, but recent warming is coherent globally (Neukom et al. 2019). As such, the persistent positive anomalies noted here are a significant shift from earlier regional variations, and suggest continued warming along current emissions trajectories (Schmidt et al. 2019).

Regional and national differences in warming rates are due to different latitudes, continentality, height and regional air circulation. They are particularly vulnerable in high latitudes due to snow, ice and albedo feedbacks. A high rate of warming has been noted since 1979, particularly in Arctic regions, at almost four times the global average (Rantanen et al. 2022). Spatial variability also reflects a lack of observational coverage or local climatic processes, so large-scale datasets of land temperature like Berkeley Earth (Rohde and Hausfather 2020) and CRUTEM5 (Osborn et al. 2021) are valuable.

The warming rates were similar or larger in the major cities than the geographical averages. There further be an urban heat-island effect with increased local warming as a result of urban expansion, less greenery, a high density of infrastructure, and heat retention. These patterns have significant public health, energy and urban resilience impacts especially in fast-growing cities. Historical observations continue to be vital to differentiate urban impacts from broader climate variability, as well as for enhanced city-level planning.

Seasonal differences show that there are not the same warming trends all year long. Rapid autumn and winter warming impacts the timing of the crop cycle, snow cover, water availability and ecosystem timing. Changes in the frequency and intensity of extreme events, such as heatwaves, droughts and unusual winter conditions, are also potential impacts of seasonal warming (Seneviratne et al. 2021).

These results are consistent with those of the large global temperature datasets and international climate assessments. Uncertainties have been enhanced in long-term records in GISTEMP (Schmidt et al. 2019) and GISTEMPv4 uncertainty ensemble adds greater confidence in recent temperature trends (Lenssen et al. 2024). The results are also in line with data from the Global Historical Climatology Network monthly dataset which is used for monitoring long-term land temperatures (Menne et al. 2018). In addition, observations-based projections also validate the ability of historical records to enhance estimates of future warming (Ribes, Qasmi, and Gillett 2021).

The policies should focus on climate-resilient urban planning, better monitoring, regional adaptation and safeguarding of highly exposed populations. There is a need to incorporate longterm observational evidence into mitigation planning and climate-risk assessment. The spatial datasets were only available until the end of 2013, and the global dataset was only available until the end of 2015, which means that recent warming was not well represented. Causality is also limited by unequal temporal coverage, missing data, land-based observations, and missing greenhouse-gas and socioeconomic data. Future studies should incorporate the latest satellite data and reanalysis data as well as land-use change, emissions, precipitation, humidity and indicators of extreme weather. Further enhancement of regional and urban temperature assessment possible using spatial regression, machine learning, and new climate projections.

5. Conclusion

The study investigated the long-term global land-surface temperature trends from historical observations at global, country, state/Province and major-city levels. The results showed that the land temperature globally rose significantly from 1750 to 2015 annually. The linear regression warming rate was 0.0458 °C per decade and Sen's slope warming rate was 0.0516 °C per decade. That the 2015 was the warmest on record and that the 1980s, 1990s, 2000s and 2010s were the four warmest decades further reinforced the warming acceleration in recent decades. The seasonal analysis indicated a noteworthy warming in all seasons with the maximum warming in autumn and winter seasons. Widespread warming was also indicated by spatial comparisons of all geographical units analysed. The mean warming rate for the country-level records was 0.0702 °C per decade; the mean rate for states or provinces was 0.0643 °C; and the rate for major cities was 0.0694 °C per decade. These fluctuations illustrate the spatial differences in warming while the warming trend is consistent. The results highlight the need for long-term temperature monitoring for identification of climate-sensitive regions and for evidence-based adaptation. The historical end point of the datasets, however, and the fact that the data for some variables are not available for the same time periods, missing observations, and lack of direct greenhouse-gas and socioeconomic variables, constrain causal interpretation. Future research should incorporate more recent satellite observations, reanalysis data, emissions, land-use information, and extreme weather data to ensure the most up-to-date and thorough regional climate change assessments.

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